National Aeronautics and
Space Administration

Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523-0273

Reply to Attn of: F-2001-17-1718

May 1, 2001

TO: All Holders of NASA/CP-2001-210389/VOL3

FROM: F/Technical Publications Office

SUBJECT: Errata Sheet for NASA/CP-2001-210389/VOL3, Dated April 2001

NASA/CP-2001-210389/VOL3, *Pilot-Induced Oscillation Research: Status at the End of the Century,* compiled by Mary F. Shafer and Paul Steinmetz, is incomplete on pages 413 to 438. The document says "Not all graphics were available for slides at time of publication," on page 413. These slides are now available and are being mailed with the document to replace pages 413 to 438 in this publication.

Please make the following change to this document. Insert the pages provided (413 to 438) to replace those that are incomplete in the document.

Staple this errata sheet inside the front cover of Volume 3 of the document.

Thank you for your cooperation.

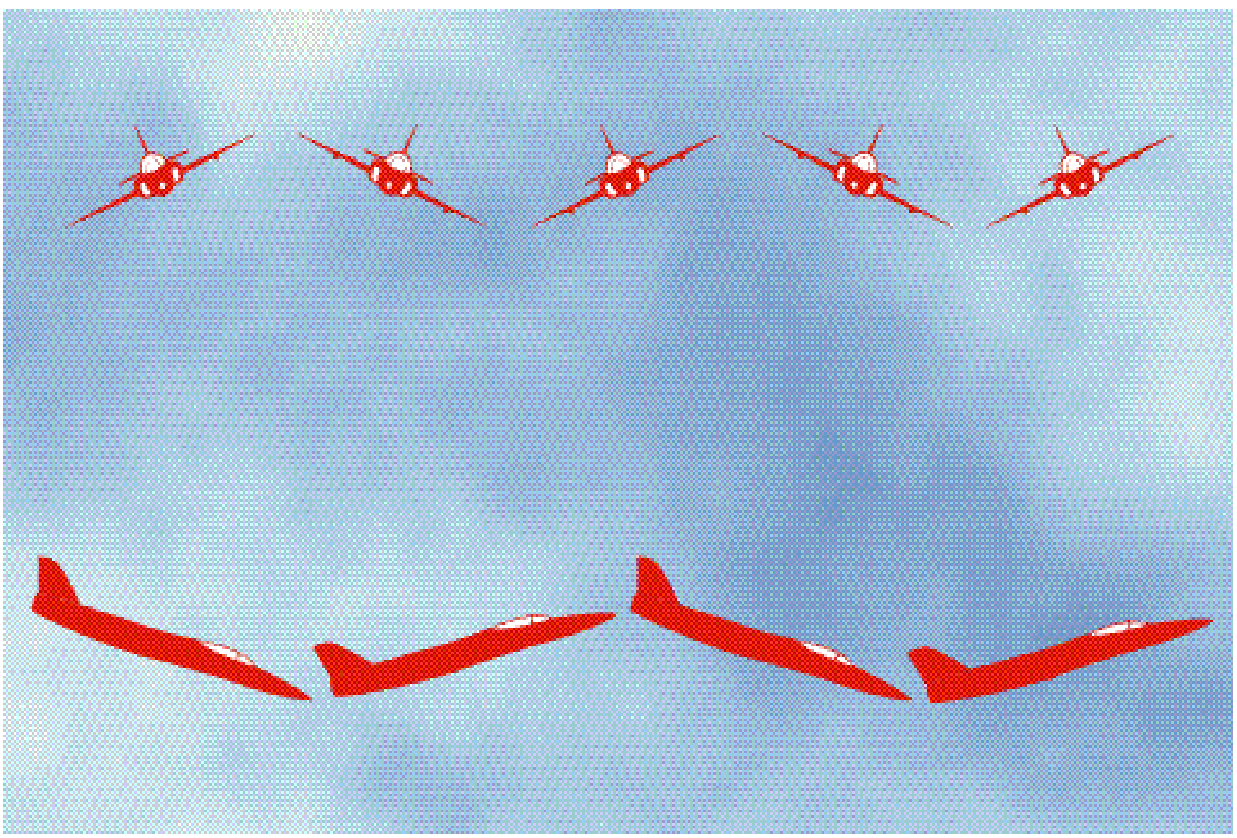
for CFM.

Camilla F. McArthur
Administrative Operations Specialist

NASA/CP-2001-210389/VOL 1 – 3

Pilot-Induced Oscillation Research: Status at the End of the Century

Compiled by Mary F. Shafer and Paul Steinmetz
NASA Dryden Flight Research Center
Edwards, California



April 2001

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NASA/CP-2001-210389/VOL1 – 3

Pilot-Induced Oscillation Research: Status at the End of the Century

Compiled by Mary F. Shafer and Paul Steinmetz
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Foreword

“Pilot-Induced Oscillation Research: The Status at the End of the Century,” a workshop held at NASA Dryden Flight Research Center on 6–8 April 1999, may well be the last large international workshop of the twentieth century on pilot-induced oscillation (PIO). With nearly a hundred attendees from ten countries and thirty presentations (plus two that were not presented but are included in the proceedings) the workshop did indeed represent the status of PIO at the end of the century.

These presentations address the most current information available, addressing regulatory issues, flight test, safety, modeling, prediction, simulation, mitigation or prevention, and areas that require further research. All presentations were approved for publication as unclassified documents with no limits on their distribution.

This proceedings include the viewgraphs (some with authors’ notes) used for the thirty presentations that were actually given as well as two presentations that were not given because of time limitations. Four technical papers on this subject that offer this information in a more complete form are also included. In addition, copies of the related announcements and the program are incorporated, to better place the workshop in the context in which it was presented.

Mary F. Shafer

CONTENTS

VOLUME 2 – SESSIONS IV – V

VOLUME 3 – SESSION VI AND APPENDICES

Session I

Modeling the Human Pilot in Single-Axis Linear & Nonlinear Tracking Tasks

Yasser Zeyada, and Ronald A. Hess
Dept. of Mechanical and Aeronautical Engineering
University of California
Davis, CA 95616

Outline

- Introduction
- Analytical Approach
  - Structural Model
  - Linear Analysis (Program PVD)
  - Nonlinear Analysis (Program PVD_{NL})
  - Improved Version of PVD_{NL} with Graphical User Interface
- Analyzing HAVE LIMITS data
- Design Example - Longitudinal Flight Control System For HARV
- Self-Report Card on "Criteria for Criteria"
- Conclusions

Introduction

- Motivation
  - "Research to develop design assessment criteria and analysis tools should focus on Category II and III PIOs….This research should combine experiments with the development of effective mathematical analysis methods capable of rationalizing and emulating the experimental results"
    - » Recommendation 6-3 *Aviation Safety and Pilot Control*, Report of the Committee on the Effects of Aircraft-Pilot Coupling on Flight Safety, NRC, 1997
- Approach
  - Extend linear, closed-loop, HQR/PIO prediction technique to vehicles with significant nonlinearities, e.g., actuator rate saturation
- Assess technique using HAVE LIMITS flight test data

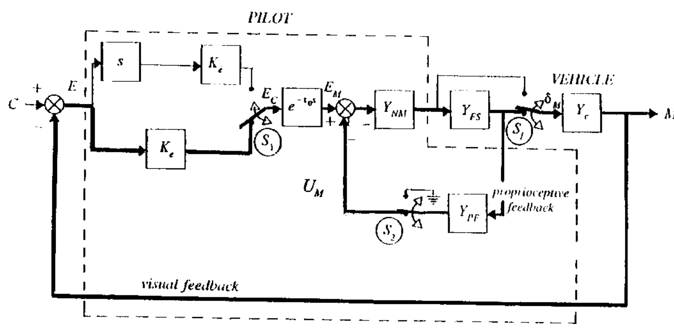
Analytical Approach

Principal Assertions

- Aircraft handling qualities, including PIO events are fundamentally <u>closed-loop phenomena</u>
- A unifying theory for handling qualities and PIO, should, therefore, adopt a <u>closed-loop perspective</u>
- A closed-loop perspective, of necessity, requires a <u>model of the human pilot</u>

Analytical Approach

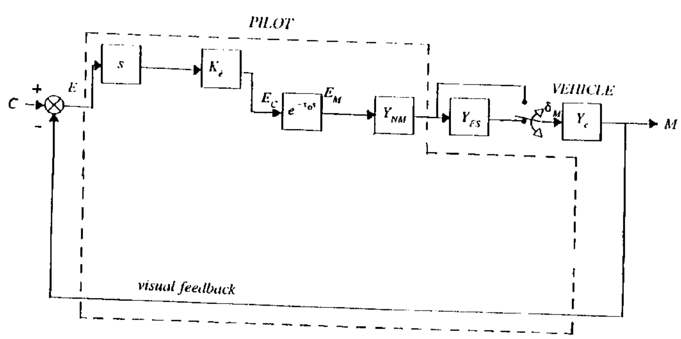
Structural Model of Human Pilot



Analytical Approach

Structural Model of Human Pilot

"Regressive Mode" - Assumed to Occur in Fully-Developed PIO



Analytical Approach

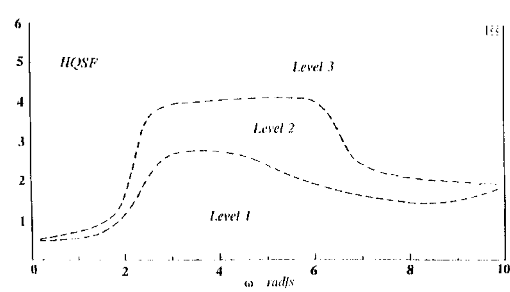
Applying Structural Model to Linear Vehicles

- Methodology developed in
  - Hess, R. A., "Unifying Theory for Aircraft Handling Qualities and Adverse Aircraft-Pilot Coupling," *Journal of Guidance, Control, and Dynamics,* Vol. 20, No. 6, 1997
- Interactive MATLAB-based computer program developed as
  - Zeyada, Y., and Hess, R. A. "PVD Pilot Vehicle Dynamics, An Interactive Computer Program for Modeling the Human Pilot in Single-Axis Linear Tracking Tasks, Dept. of Mechanical and Aeronautical Engineering, UC Davis, 1998.

Analytical Approach

The Handling Qualities Sensitivity Function (HQSF)

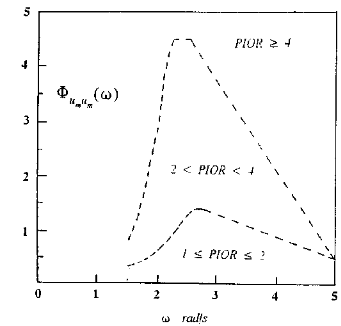
- Given model of vehicle dynamics, PVD allows creation of a Structural Model of the pilot
- The HQSF is defined by $|U_M/C|$, after normalized by gain K_e in model
- Using NT-33A and TIFS flight test data, bounds on $|U_M/C|$ obtained which could delineate handling qualities levels



Analytical Approach

The Power Spectral Density of U_M ($\Phi_{u_m u_m}(\omega)$)

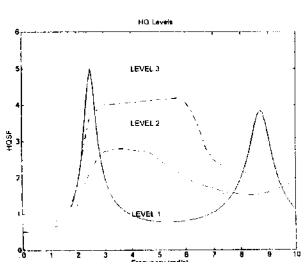
- Given model of vehicle dynamics, PVD allows creation of a Structural Model of the pilot
- The power spectral density of U_M, after normalized by gain K_e^2 in model, is obtained
- Using NT-33A and TIFS flight test data, bounds on $\Phi_{u_m u_m}(\omega)$ obtained which could delineate PIOR "levels"



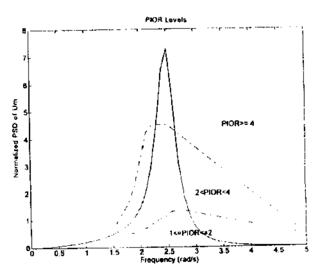
Analytical Approach

Example - A LAHOS Config. with 0.2 s time delay added

Handling Qualities Level



Pilot-Induced Oscillation "Level"



Analytical Approach

Applying Structural Model to Nonlinear Vehicles
("Nuisance" Nonlinearities)

- Methodology developed in
  - Hess, R. A., and Stout, P. W., "Assessing Aircraft Susceptibility to Nonlinear Aircraft-Pilot Coupling/Pilot-Induced Oscillations, *Journal of Guidance, Control and Dynamics, Nov.-Dec. 1998, pp. 957-965*)
- Interactive MATLAB/Simulink-based computer program developed as
  - Zeyada, Y., and Hess, R. A., "PVD_{NL} Pilot/Vehicle Dynamics $_{NonLinear}$ An Interactive Computer Program for Modeling the Human Pilot in Single-Axis Linear and Nonlinear Tracking Tasks, Dept. of Mechanical and Aeronautical Engineering, UC Davis, 1998.

Analytical Approach

- No fundamental changes in theoretical approach….normalized HQSF and $\Phi_{u_m u_m}(\omega)$ still used, but obtained from nonlinear Simulink simulation
- HQSF now obtained as

$$HQSF = \frac{\left| \int_0^T u_m(t) e^{-j(\omega t)} dt \right|_{\omega = \omega_i}}{\left| \int_0^T c(t) e^{-j(\omega t)} dt \right|_{\omega = \omega_i}} \cdot \left| \frac{1}{|K_e|} \right| \quad i = 1,2,\ldots,50$$

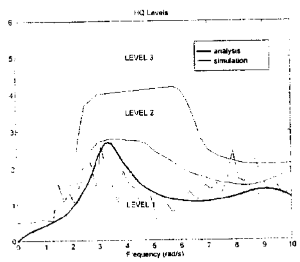
- $\Phi_{u_m u_m}(\omega)$ now obtained as

$$\Phi_{u_m u_m}(\omega) = \left[\frac{4^2}{\omega^4 + 4^2} \right] \cdot HQSF^2$$

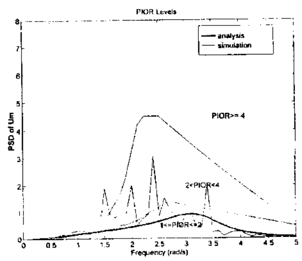
Analytical Approach

Example - A LAHOS Config. with amplitude and rate-limited elevator actuator

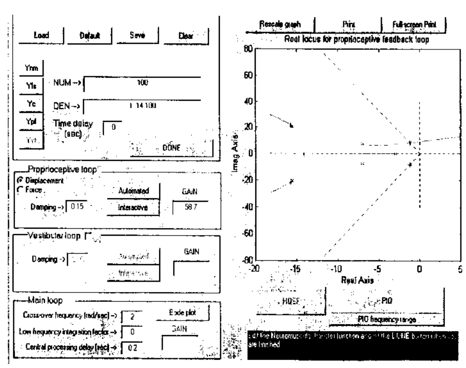
Handling Qualities Level



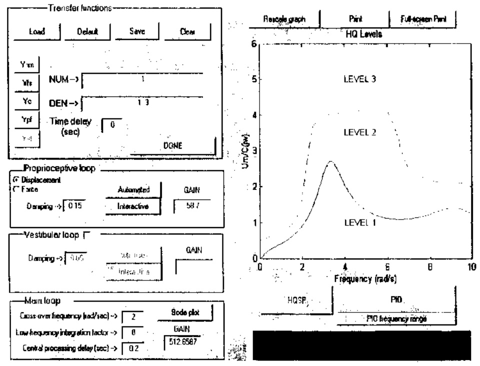
Pilot-Induced Oscillation "Level"



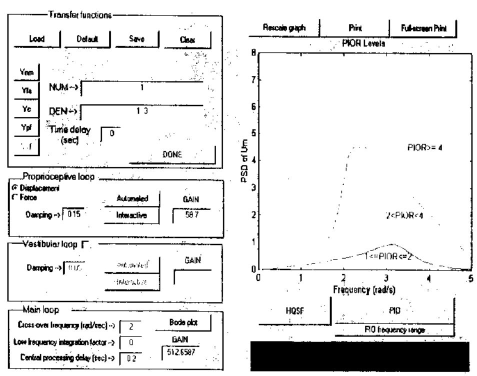
Improved Version of PVD_{NL} with GUI



Improved Version of PVD_{NL} with GUI



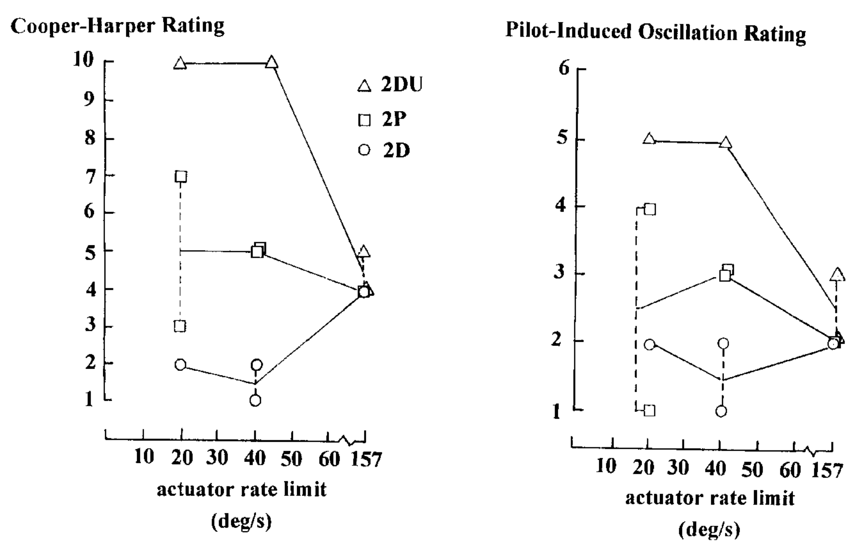
Improved Version of PVD_{NL} with GUI



HAVE LIMITS Flight Tests

- USAF-Sponsored flight tests using (for the last time) the NT-33A variable stability aircraft
- Goal: Evaluation of effects of actuator rate limiting on longitudinal handling qualities and PIO
- Three configurations evaluated:
  - 2D (stable unaugmented airframe
  - 2P (essentially 2D with stick filter)
  - 2DU (unstable unaugmented airframe, similar to 2D when augmented)
- Two HUD pitch-attitude commands utilized
  - sum of sinusoids
  - discrete, step-like

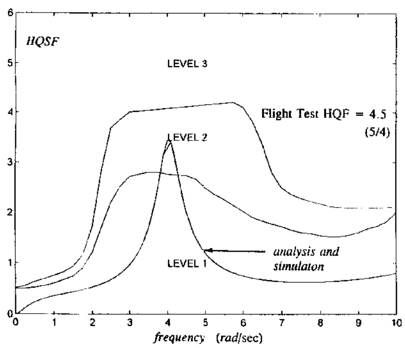
HAVE LIMITS Flight Tests (Pilot 3)



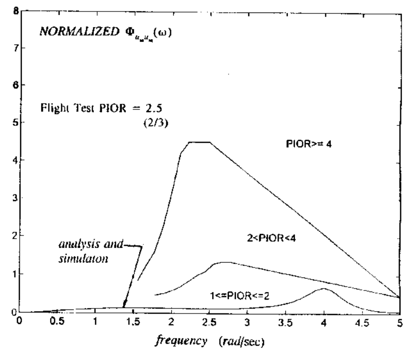
Analyzing HAVE LIMITS data

Configuration 2DU with rate limit = 157 deg/s

Handling Qualities Level



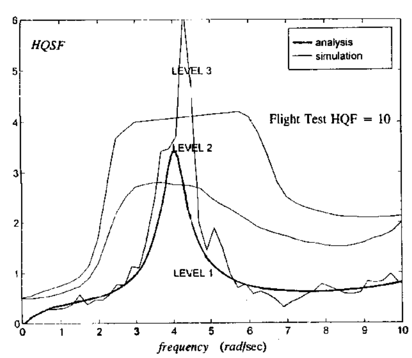
Pilot-Induced Oscillation "Level"



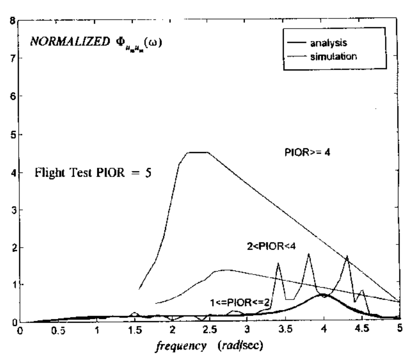
Analyzing HAVE LIMITS data

Configuration 2DU with rate limit = 60 deg/s
(pilot/vehicle system unstable @ 40 deg/s)

Handling Qualities Level



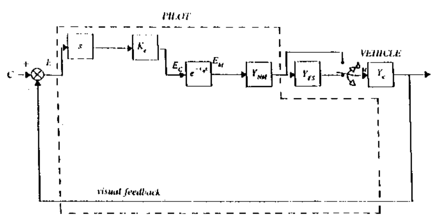
Pilot-Induced Oscillation "Level"



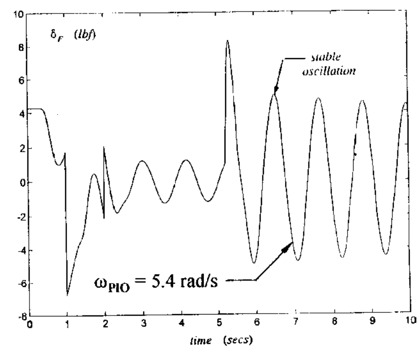
Analyzing HAVE LIMITS data

Configuration 2DU with rate limit = 53 deg/s
(minimum rate limit for pilot/vehicle stability)

Rate-tracking Structural Model

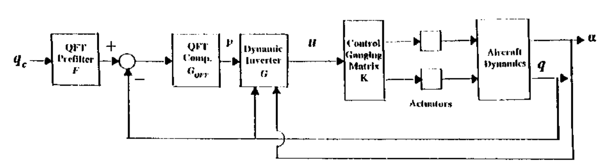


Predicted (fully-developed) PIO



Design Example
Longitudinal Control of HARV

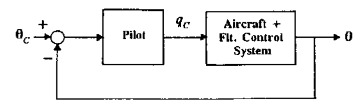
- Control structure



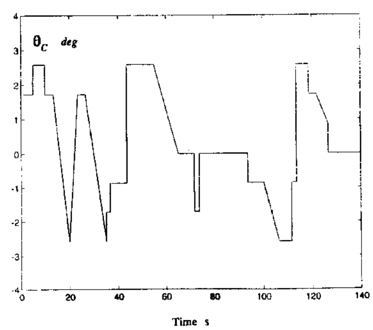
- Reduced-order model
  - only rigid-body vehicle dynamics considered - (dynamics of two actuators ignored)
  - simple two-state reduced-order model results (short-period vehicle model used)

Nonlinear Pilot/Vehicle Analysis

- Actuator rate and amplitude limiting must be considered in final handling qualities evaluation
- Pilot/vehicle system



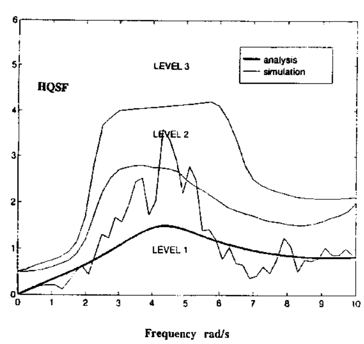
- Pitch command

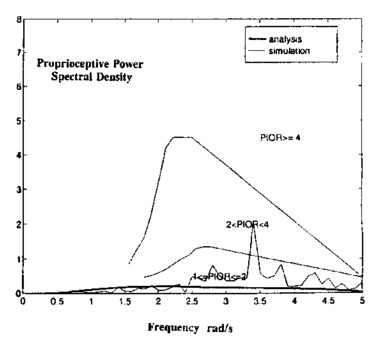


Nonlinear Pilot/Vehicle Analysis

Initial predicted handling qualities and PIO levels
using Structural Pilot Model and program PVD_{NL}

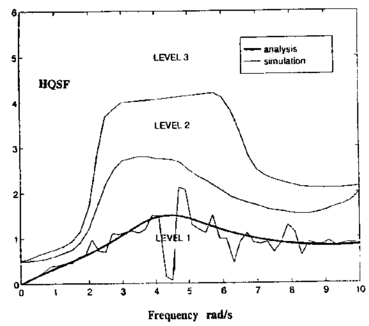
Flight Cond: Mach No. = 0.3, Alt. = 26.000 ft
full ± 20% perturbations on vehicle $\mathbf{A}_r$ and $\mathbf{B}_r$ matrix elements

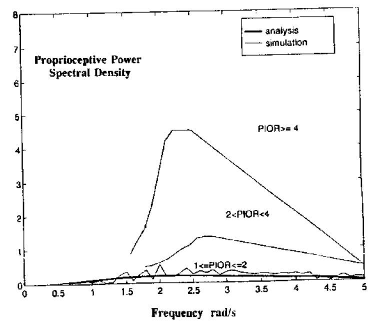




Nonlinear Pilot/Vehicle Analysis

Predicted handling qualities and PIO levels
after addition of anti-windup logic in $G_{QFT}(s)$





Self -Report Card on
Criteria for Criteria

Definitions taken from NRC PIO report

- ***Validity:*** *Implies that a criterion embodies properties and characteristics that define the environment of interest…criterion must relate to closed-loop, high-gain, aggressive, urgent and precise pilot-control behavior*

  Grade = 7.5/10
- ***Selectivity:*** *Demands that criterion differentiate sharply between "good" and "bad" systems…in context of PIO prediction, must distinguish between configurations that may be susceptible to severe PIOs from those that are not*

  Grade = 7/10
- ***Ready Applicability:*** *requires that criterions be easily and conveniently applied*

  Grade = 6.5/10 (Original PVD_{NL})

  =7.5/10 (PVD_{NL} with GUI)

Conclusions

- Unifying theory for handling qualities and PIO can be offered for both linear and nonlinear (nuisance nonlinearity) systems

- Structural Pilot model, implemented in a computer-aided design program provided predictions of handling qualities levels and PIOR levels which compared well with those from HAVE LIMITS flight tests

- Methodology could be said to receive passing grade in "Criteria for Criteria"

Bandwidth Criteria for Category I and II PIOs

David G. Mitchell
Hoh Aeronautics, Inc.

David H. Klyde
Systems Technology, Inc.

Pilot Induced Oscillation Research Workshop
NASA Dryden Flight Research Center
6 April 1999

Background

- Phase II SBIR from Air Force Research Labs
  - Development of Methods & Devices to Predict & Prevent PIO
  - Contract monitor is Tom Cord
  - In process of writing final report
- Goals:
  - Gather data (Lockheed Martin, Northrop Grumman, McDonnell Douglas subcontractors)
  - Analyze all available PIO data
  - Develop criteria for prevention by design
  - Develop test methods for detection in flight test
  - Develop devices for real-time monitoring and detection

Outline

- Pitch criteria based on airplane Bandwidth for
  - Handling qualities
  - PIO
- Apply research, experimental, operational data
- Compare Smith-Geddes, Gibson, Neal-Smith criteria
- Bandwidth criteria for Category II PIO
- Control/response sensitivity and PIO
- Extension to roll axis
- Recommendations

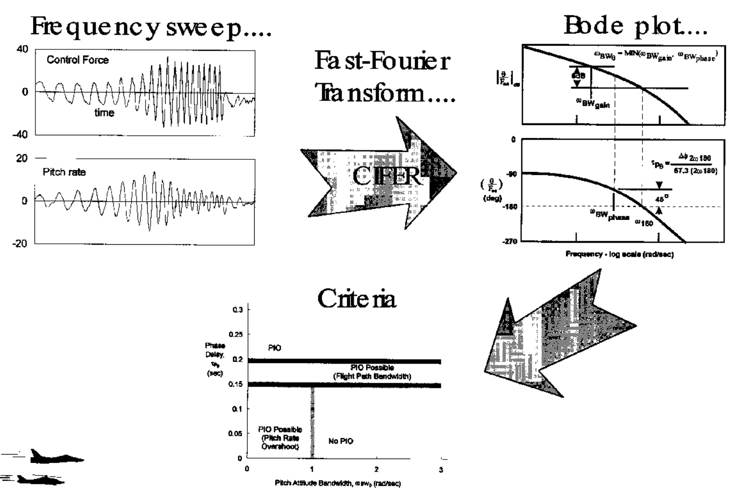
Analytical Criteria

- Category I PIOs (linear):
  - Many criteria exist
  - Bandwidth-based criteria show most promise
    - AIAA-98-4335 show them to be effective
    - Amenable to initial design through flight test
- Category II PIOs (rate limiting):
  - Only a handful of criteria
  - Most are complex to apply
    - Require closed-loop analysis
    - Applicable to analytical models only, not in flight
    - Must make assumptions about pilot, frequency, or amplitude
  - Recent work on Bandwidth criteria shows promise

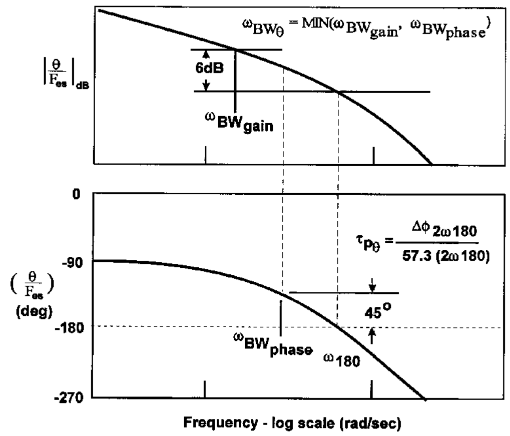
Handling Qualities Criteria

- Criteria developed for draft MIL standard (AFWAL-TR-82-3081, 1982)
  - Requirements more stringent than "classical" (CAP) criteria
  - Almost didn't make it into MIL-STD-1797 (1987)
- Primary short-term response criteria in rotorcraft handling-qualities standard ADS-33D-PRF
- For airplanes, adopted revised version of Gibson's requirements on dropback/overshoot
  - Relaxed Bandwidth limits (WL-TR-94-3162)
  - USAF TPS project found dropback untestable in flight (AFFTC-TR-95-78)
  - Dropback secondary in importance to pitch rate overshoot
  - Current criteria use frequency-domain measure of overshoot

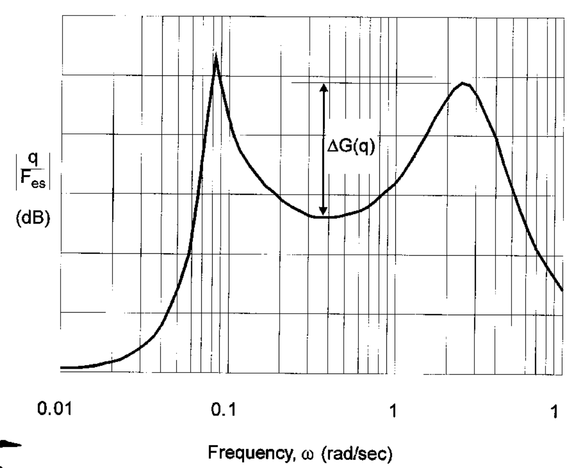
Process for Obtaining Bandwidth Information from Flight



Attitude Bandwidth Parameters

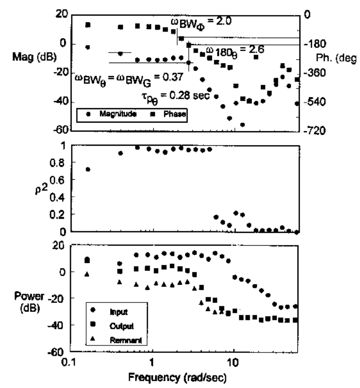


Pitch Rate Overshoot

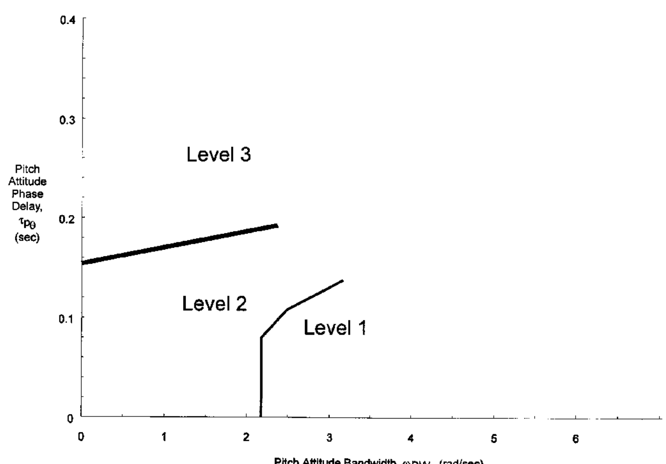


Nonlinearities Can Cause Data Quality to Degrade

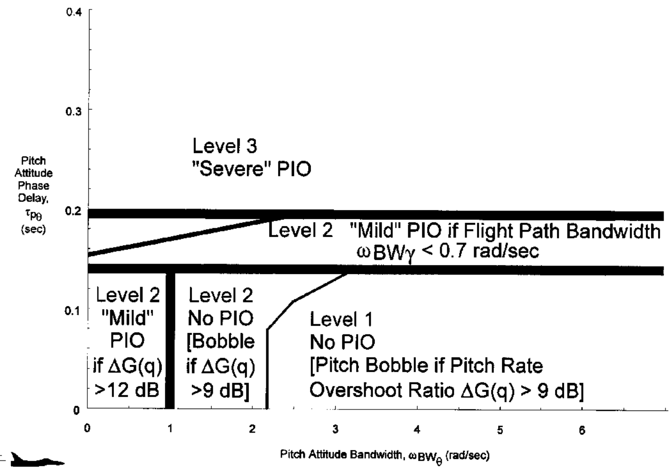
- Example data from in-flight frequency sweep
- Coherence drops as a result of rate limiting
  - ρ^2 is a measure of *linear* correlation between input and output
- Input power high
- Frequency response looks reasonable
- Examined in AIAA-99-0639 (Reno)



Bandwidth Criteria for Handling Qualities (Fighters -- Landing)

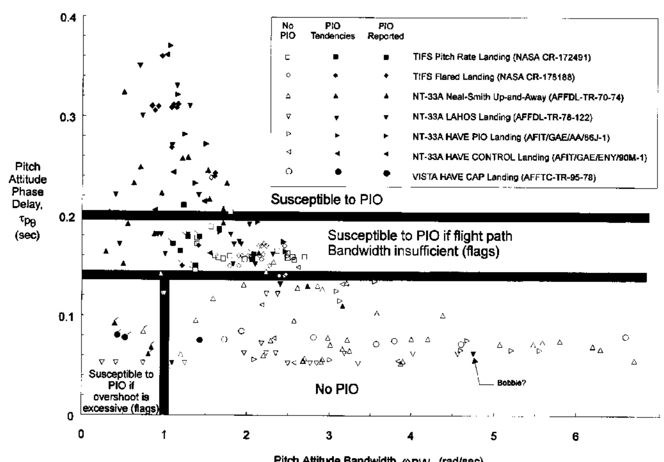


Bandwidth Criteria for PIO (Fighters -- Landing)



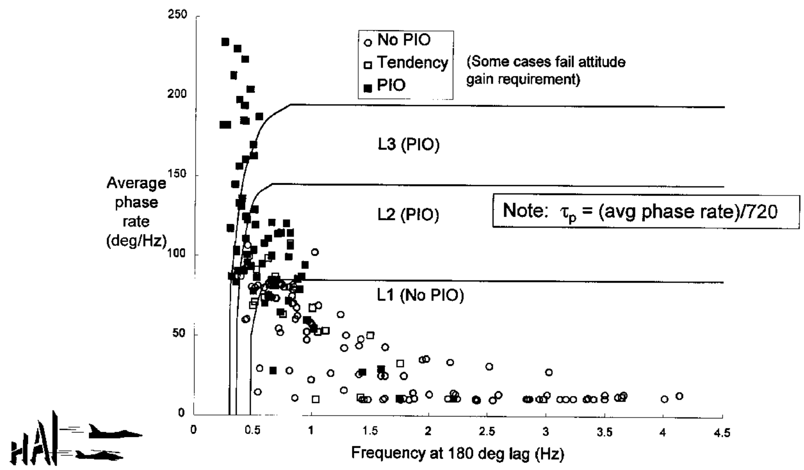
Criteria Applied to Research Data

Successful on 188 of 207 (91%) [78 of 91 PIOs (86%)]



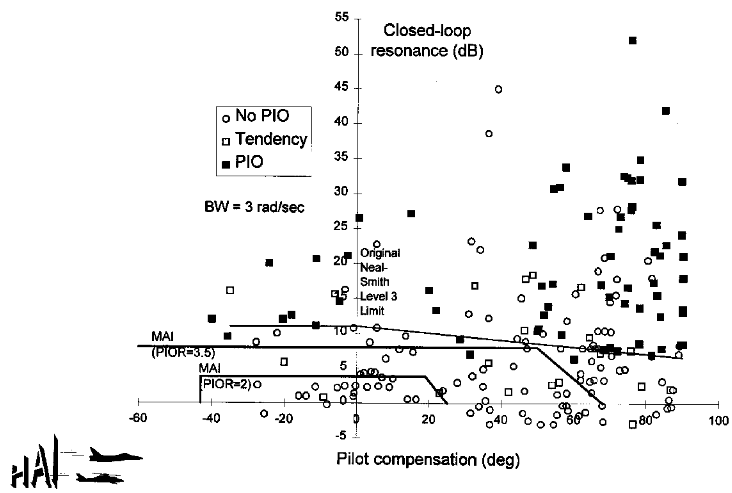
Gibson Criteria (Research Data)

166 of 207 cases (80%) [66 of 91 PIOs (73%)]



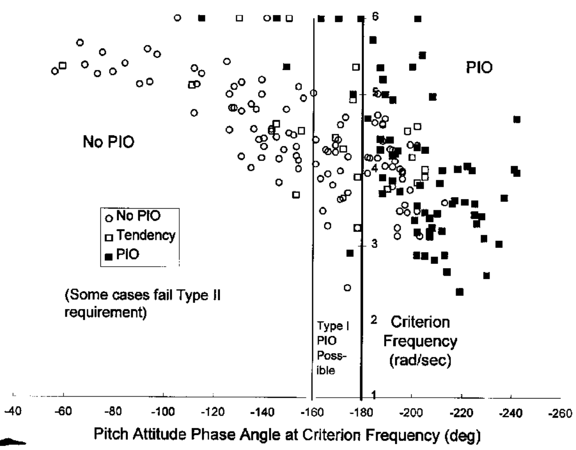
Neal-Smith Criteria (Research Data)

158 of 207 cases (76%) [75 of 91 PIOs (82%)]



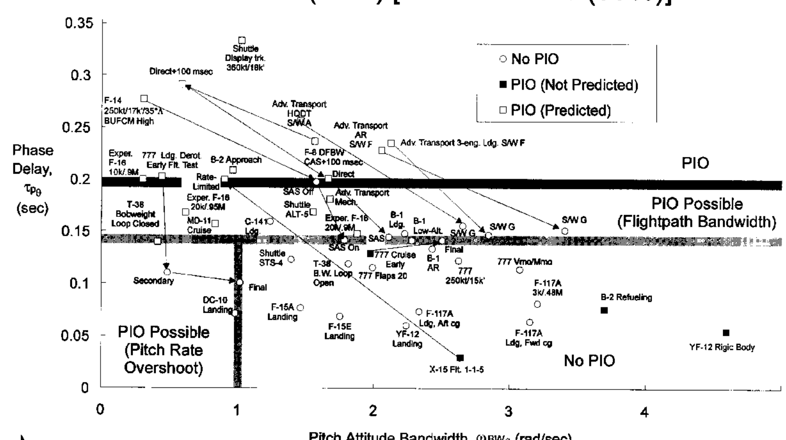
Smith-Geddes Criteria (Research Data)

133 of 207 cases (64%) [82 of 91 PIOs (90%)]



Bandwidth Criteria Applied to Real Airplanes

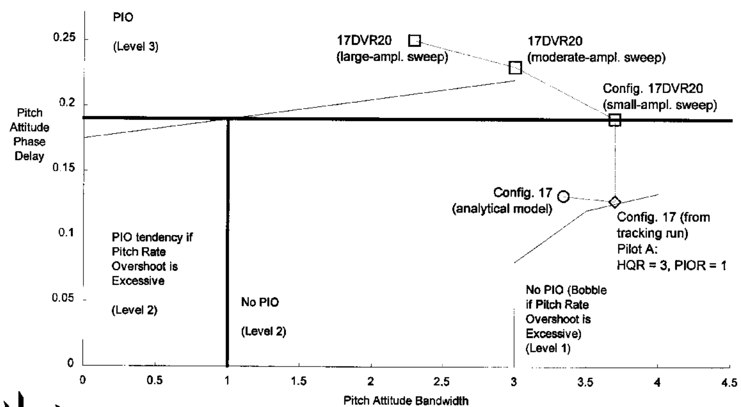
45 of 49 cases (92%) [20 of 24 PIOs (83%)]



Application to Rate-Limited Configurations

Example: Frequency sweeps from LAMARS simulation

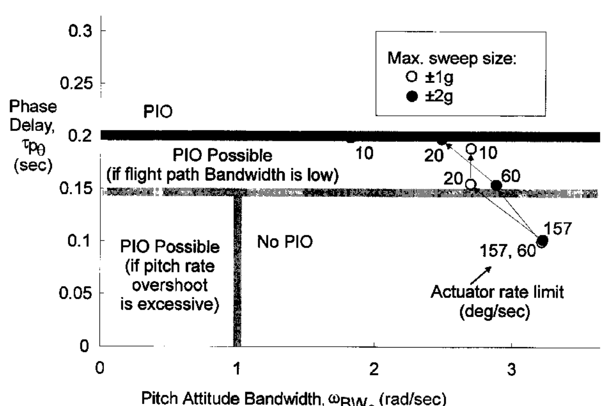
(20-deg/sec RL, unstable open-loop; 1 of 5 pilots encountered divergent PIOs)



Application to Rate-Limited Configurations

Example: Config. 2D from HAVE LIMITS TPS Project

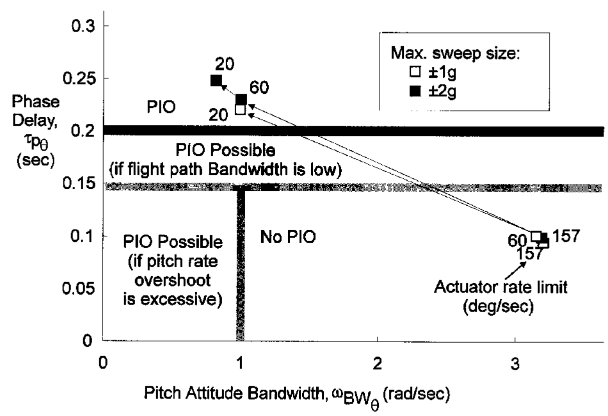
(RL on stable bare airplane; no PIOs reported for discrete tracking task)



Application to Rate-Limited Configurations

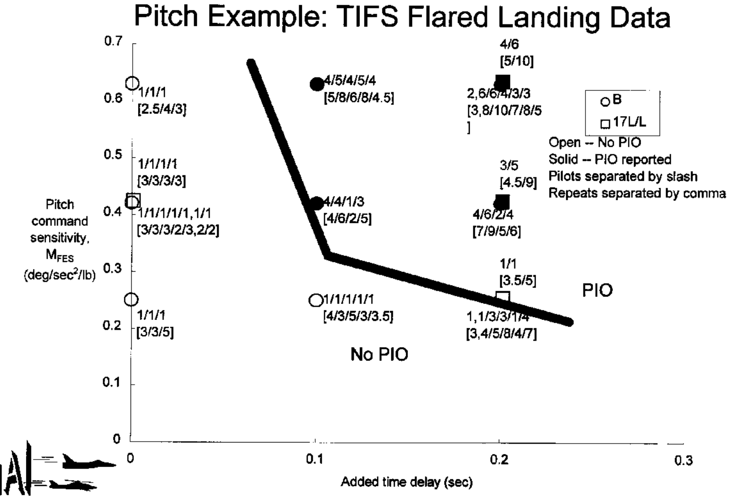
Example: Config. 2DU from HAVE LIMITS TPS Project

(Unstable open-loop; divergent PIOs for RL of 60 deg/sec and below)



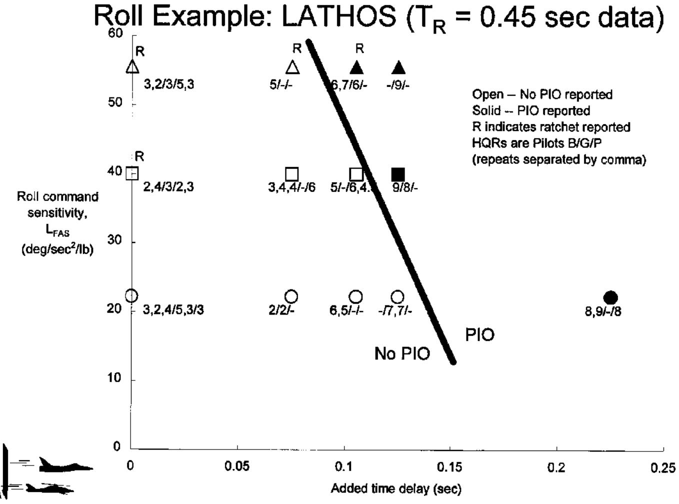
Inappropriate Control/Response Sensitivity Contributes to PIO

Pitch Example: TIFS Flared Landing Data



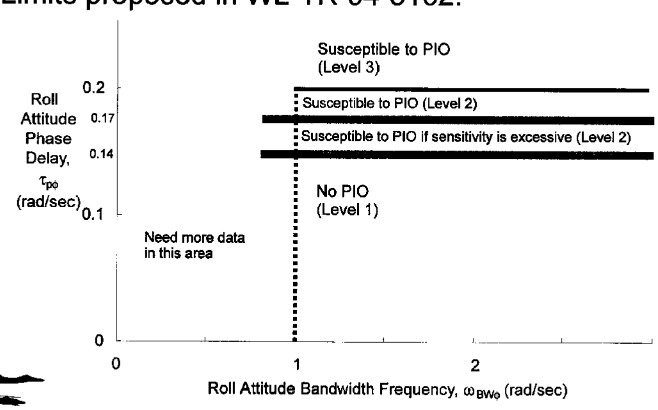
Inappropriate Control/Response Sensitivity Contributes to PIO

Roll Example: LATHOS (T_R = 0.45 sec data)



Airplane Bandwidth Criteria for Roll

- Much smaller data base
  - Not as many real experiences
  - Most research experiments did not record PIO ratings
- Limits proposed in WL-TR-94-3162:



Recommendations

- Apply criteria as early in development as possible
- Focus especially on Phase Delay limits
  - No greater than 0.14 sec in pitch or roll
- If feel system dynamics are not known or are known to be very good, limits excluding feel system are
  - No greater than 0.09 sec in pitch or roll
- Use criteria for all amplitudes of control input, up to maximum possible
  - Examine frequency-sweep results if coherence drops

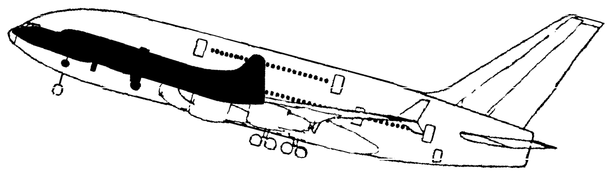
PHANTOM WORKS

Stability, Control & Flying Qualities

Criteria for Category I PIOs of Transports Based on Equivalent Systems and Bandwidth

Ken F. Rossitto and Edmund J. Field

Boeing, Long Beach



PIO Workshop

NASA Dryden

April 6–8, 1999

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NASA Dryden PIO Workshop / 6-8 Apr-99 / EJF / 1

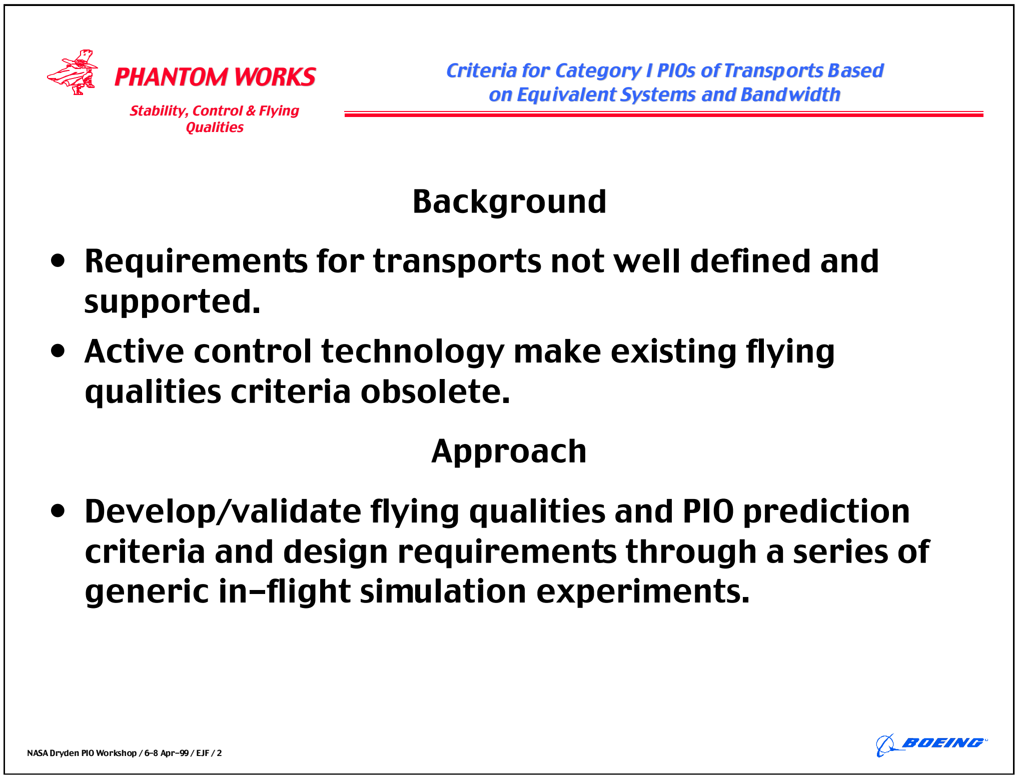
Between 1992 and 1994 The Boeing Company, Long Beach, performed a series of flying qualities experiments concerning transport aircraft. The experiments were performed in cooperation with the USAF (focal point Dave Leggett) and NASA Langley (focal point Bruce Jackson). Both government partners provided evaluation pilots, the USAF also contributed funding for flight evaluations.

The purpose of the experiments was to generate a longitudinal flying qualities database that could be used for criteria development. The flying qualities results of these experiments will be presented in a paper at the AIAA Atmospheric Flight Mechanics conference this August in Portland, Oregon[1].

The results of the experiments have also been analyzed to identify PIO tendencies in the aircraft configurations evaluated. Results from these analyses will be presented here.

After reviewing the background to the experiments and the approach taken, the evaluation task will be discussed. The results, as they apply to flying qualities criteria, will then be presented. Finally, PIO prediction criteria based on the results will be presented.

1. Field, Edmund J., and Rossitto, Ken R., "Approach and Landing Longitudinal Flying Qualities for Large Transports Based on In-Flight Results", AIAA-99-4095, presented at the AIAA Atmospheric Flight Mechanics conference, Portland, Oregon, August 1999.



Background

Flying qualities requirements for transport aircraft are not well defined and supported:

• FARs and JARs are very limited

•Military specifications are more fighter oriented

•Limited database on 1 million pound airplanes.

Additionally, active control technology makes existing flying qualities criteria, where they exist, obsolete.

Approach

To develop / validate criteria and design requirements through a series of generic in-flight simulation experiments. Need:

•Preferred response type

•Pitch axis dynamics

•Pitch axis time delays

PHANTOM WORKS

Stability, Control & Flying Qualities

Criteria for Category I PIOs of Transports Based on Equivalent Systems and Bandwidth

USAF / Calspan Total In-Flight Simulator (TIFS)

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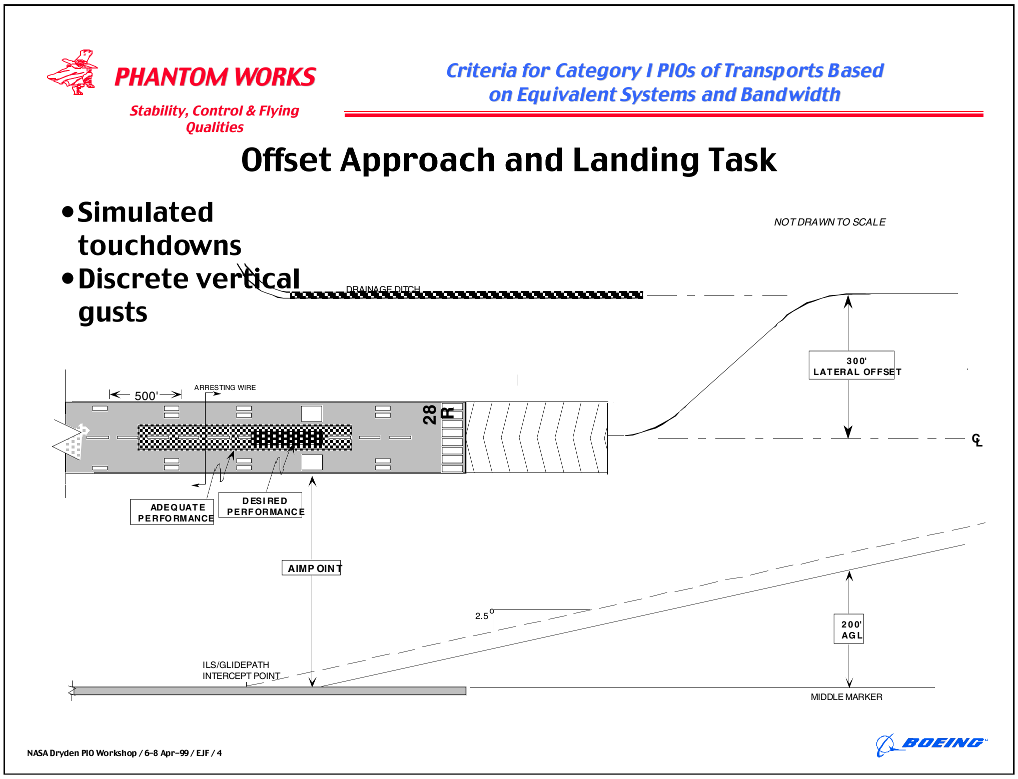
The facility used for the experiment was the USAF Total In-Flight Simulator (TIFS), operated by Calspan, Buffalo, NY.

Most approaches were flown into Niagara Airport, though some were flown at Buffalo.



The evaluation task used for the experiment was an offset approach and landing. The lateral offset of 300 feet was corrected at around 200 feet AGL and required an additional pitch axis "duck under" to land on the aim point.

Desired performance criteria were:

Touchdown between 1000 and 1500 feet past threshold

Touchdown within 10 feet of centerline

Touchdown sink rate between 0 and 4 feet/second

No PIO

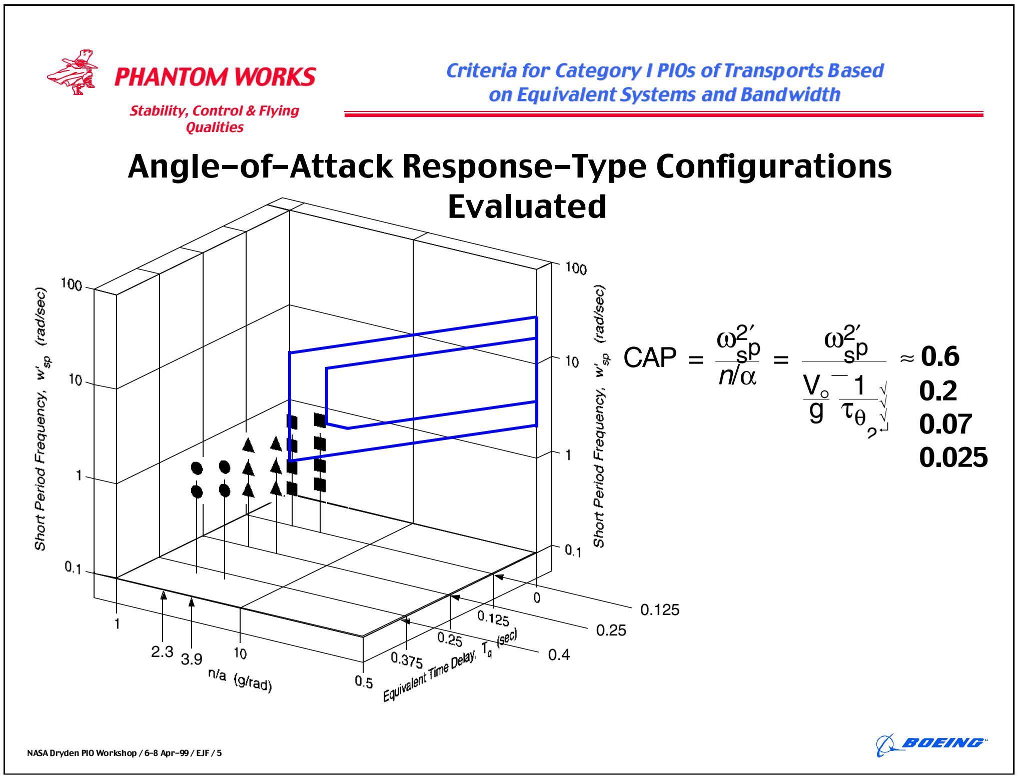
Adequate performance criteria were:

Touchdown between 750 and 2250 feet past threshold

Touchdown within 27 feet of centerline

Touchdown sink rate between 4 and 7 feet/second

All data reported here resulted from simulated landings performed to match the pilot's correct "eye-height" at the landing point in the simulated aircraft.

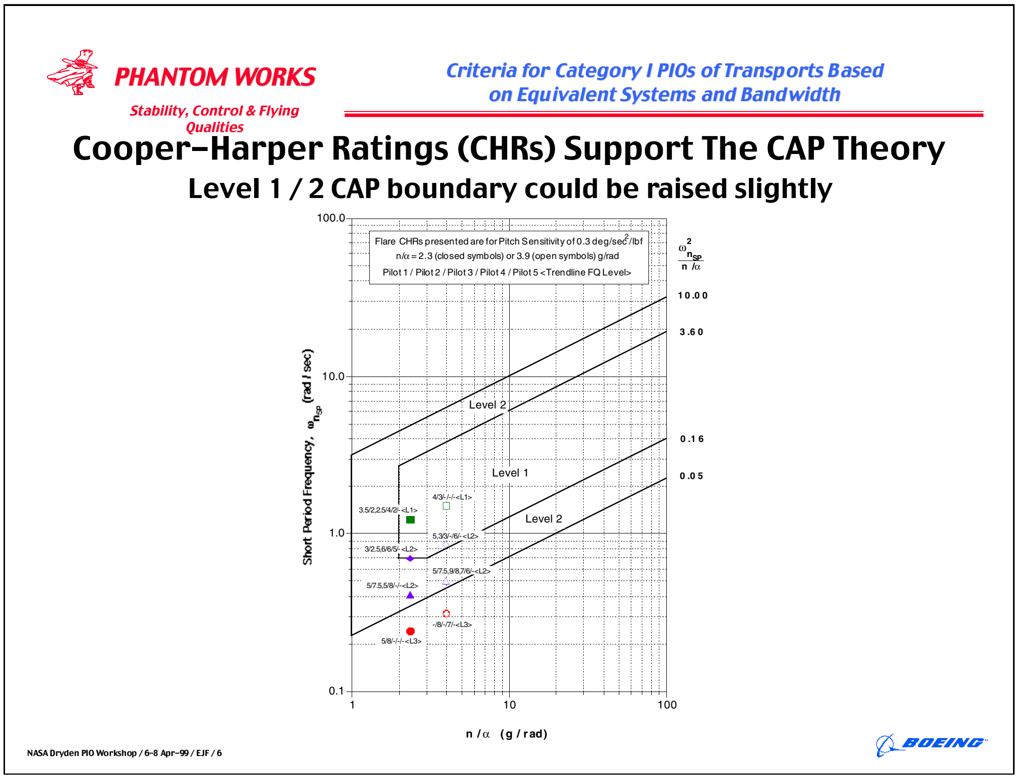


The flying qualities experiment evaluated a range of different dynamics for a one million pound transport aircraft. The bulk of the data collected was for an angle-of-attack (or conventional) response-type. Only that data will be presented here.

Experiment variables were:

n/α:	2.3 and 3.9
CAP:	0.025, 0.07, 0.2 and 0.6
Time delay:	125, 250 and 400 msec

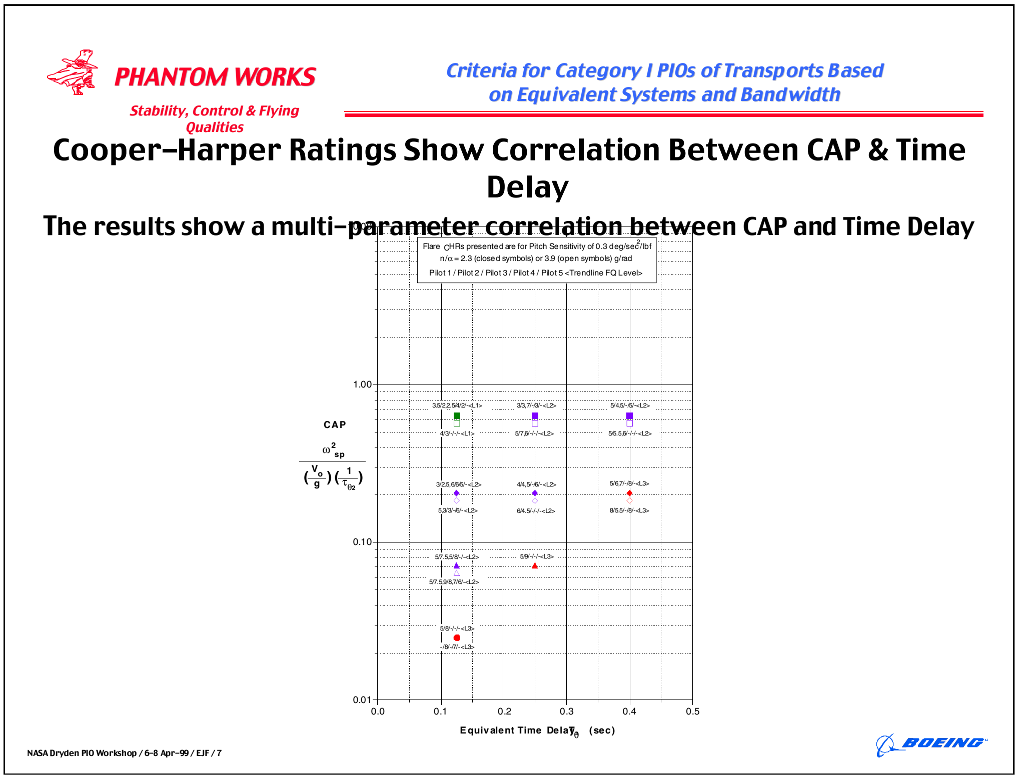
Additionally, two pitch sensitivities were evaluated. The majority of the evaluations were with a pitch sensitivity of 0.3 deg/s^2/lb, and only that data is presented. A pitch sensitivity of 0.45 deg/s^2/lb was also evaluated for selected configurations.



The results for the configurations with zero added time delay (125 msec baseline configurations) are plotted on the existing Military specification CAP boundaries. Cooper-Harper ratings for each pilot are presented together with a "Trendline FQ Level". This trendline flying qualities level was determined from the individual ratings, the median rating and pilot comments. Additionally, experimental issues, such as quality of model following in the TIFS, were assessed. These trendline flying qualities levels have been fixed and are now used for development of flying qualities criteria.

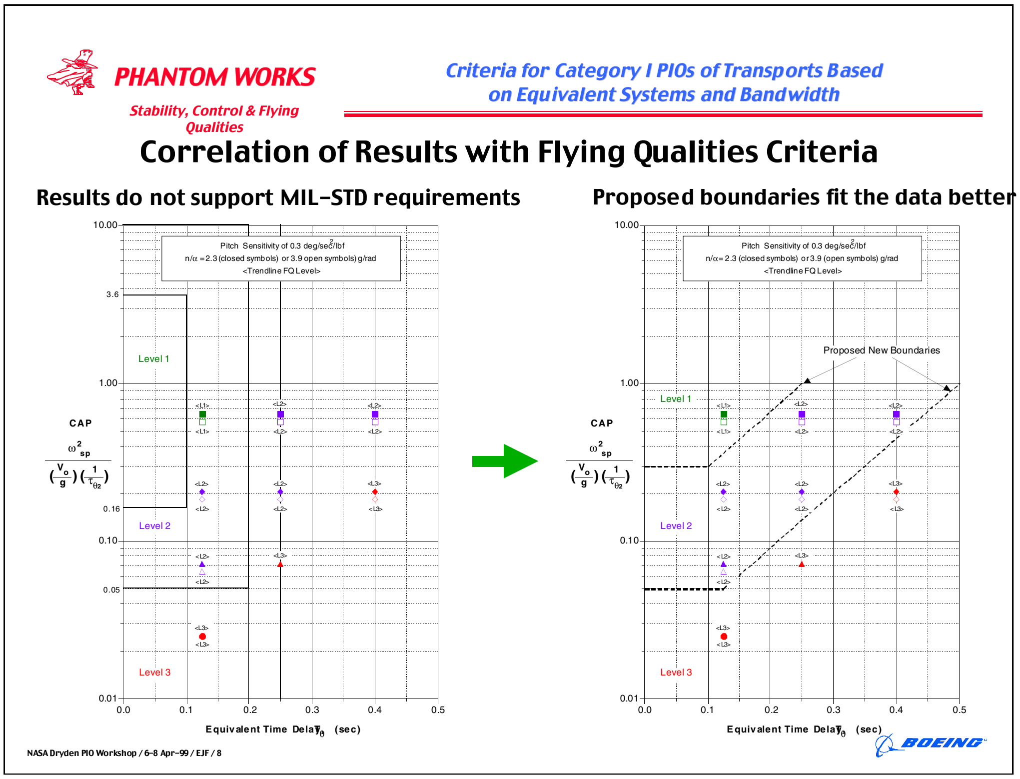
The trendline flying qualities levels support the theory behind the CAP criterion. Additionally they support the raising of the Level 1/2 boundary.

For more details and discussion of these results refer to the AIAA paper mentioned above.



With the time delay configurations added CAP is plotted against Time Delay. Note that the two values of n/α yield slightly different values of CAP, except for the lowest value of CAP (represented by the circle) which both share the same value.

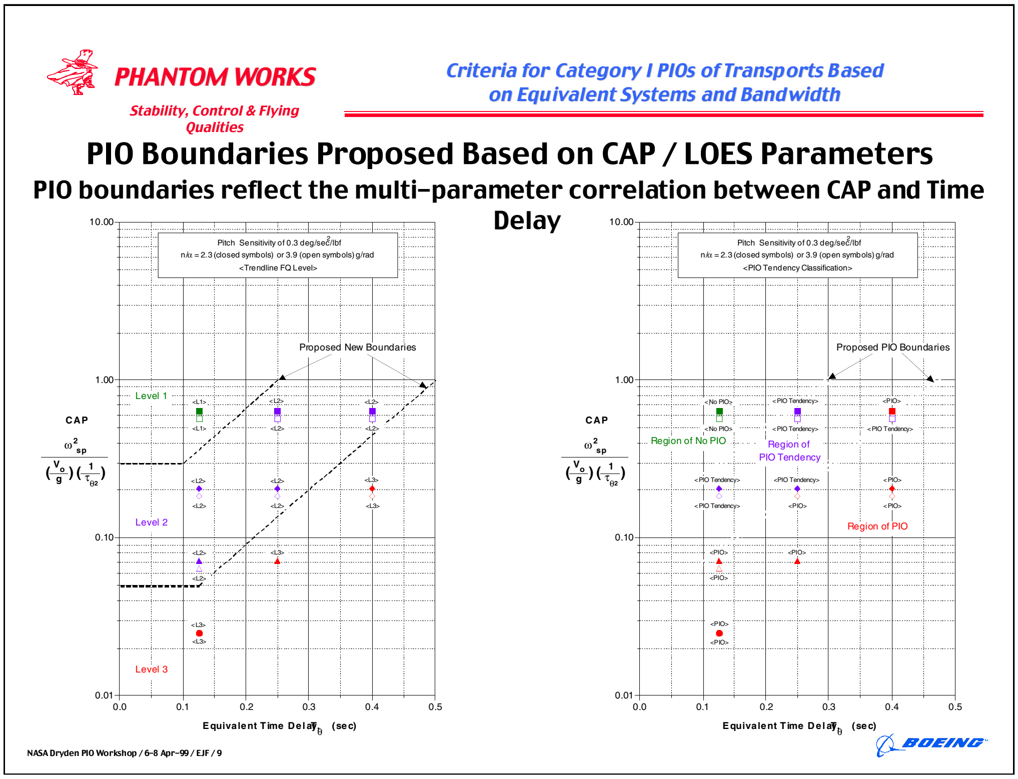
It is clear from this plot that there is a multi-parameter link between CAP and Time Delay in the pilots' perception of flying qualities.



When the MIL-STD 1797 flying qualities level limit boundaries are added to the plot of CAP versus time delay (left hand plot) it is clear that these requirements neither match the data nor allow for the observed multi-parameter correlation between CAP and time delay.

New flying qualities boundaries have been developed and are proposed (right hand plot). These boundaries reflect the multi-parameter correlation between CAP and time delay that were identified from pilot ratings and comments. These trends have also been observed the results of other ground-based simulation experiments.

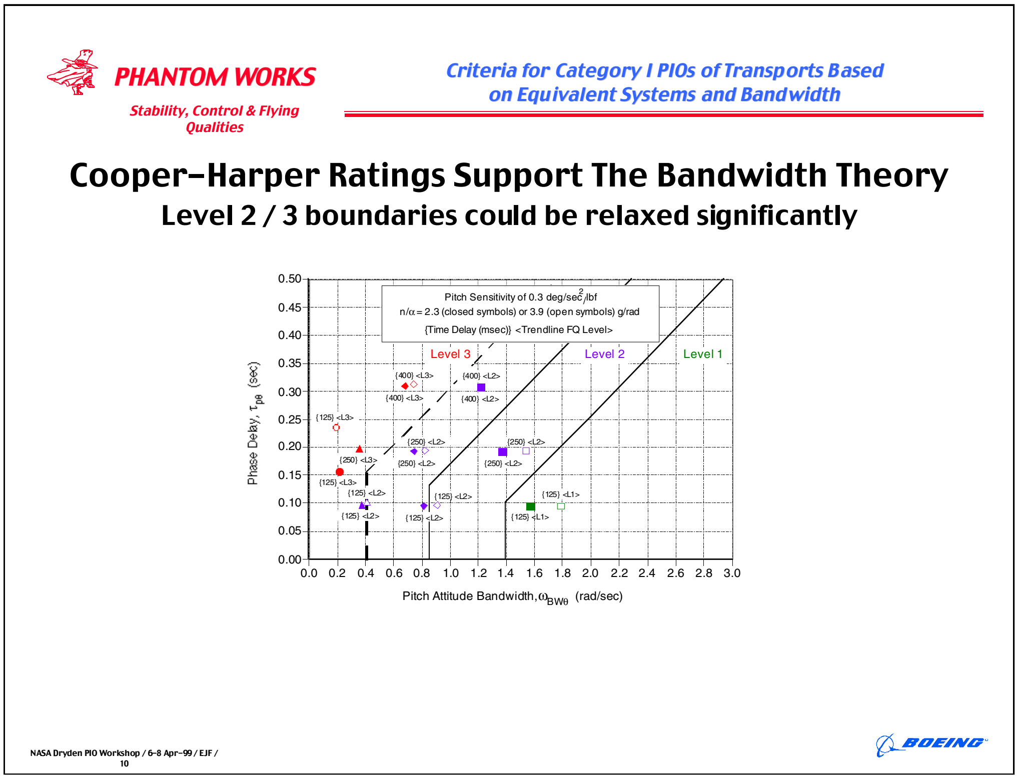
Note: For clarity only the "Trendline Flying Qualities Level" is presented on all charts from here.



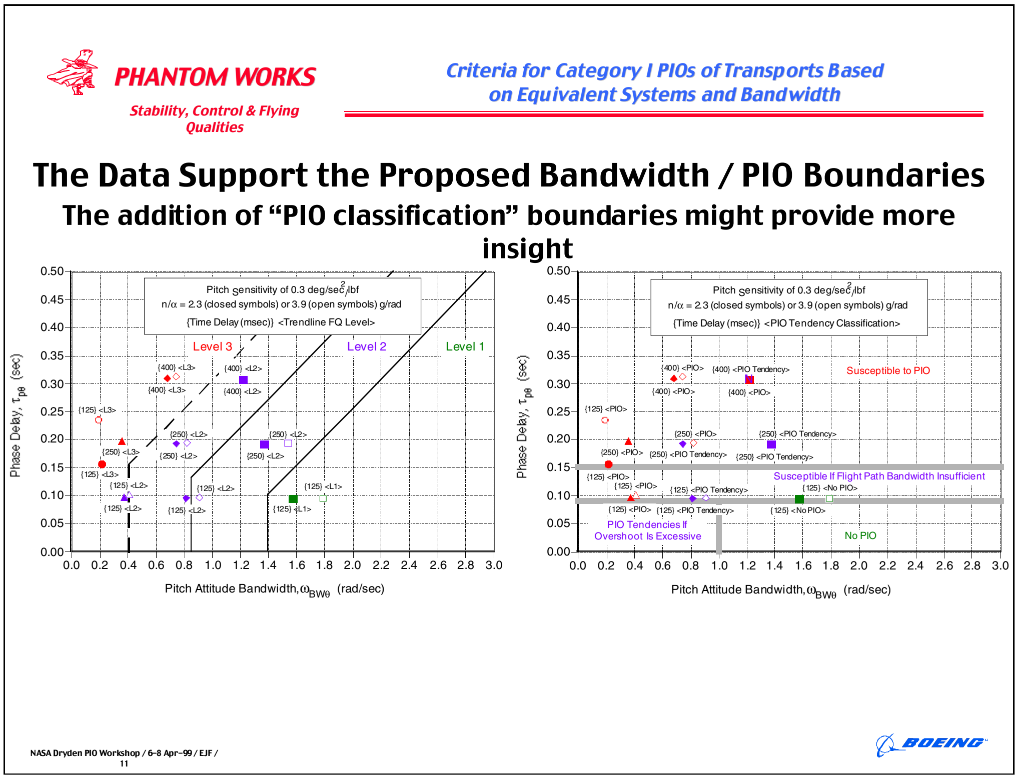
Analysis of the PIO ratings and pilot comments from the experiments led to the awarding of a “PIO Tendency Classification” to each configuration. This was achieved in the same way as the earlier “Trendline Flying Qualities Level”. Each configuration was awarded a classification of “No PIO”, “PIO Tendency” or “PIO”.

Boundaries delineating the regions of these classifications reflect the same multi-parameter correlation between CAP and time delay as was observed in the flying qualities analysis. The limit of “No PIO” boundary appears to be slightly more relaxed than the Level 1 limit boundary. This is based upon the configurations for a CAP of 0.6 and time delay of 250 msec. These configurations exhibited only marginal PIO tendency, but sufficient to exclude them from classification of “No PIO”. Hence the boundary was drawn close to these configurations.

However, the “PIO” limit boundary appears more stringent than the Level 2 limit boundary.



When the results of the flying qualities experiment are plotted on the Bandwidth Criterion, it is clear they support the theory of the criterion. However, they also support the significant relaxation of the Level 2/3 boundary.



When the PIO tendency classifications are plotted on the Bandwidth requirement they support the boundaries delineating the different PIO susceptibility regions. This may not be immediately obvious, but the following discussion will show this.

The two configurations that were classified "No PIO" fall just above the lower limit of the "Susceptible if Flight Path Bandwidth Insufficient" zone. For these configurations the flight path bandwidth was sufficient, and so they correlate with the criterion.

The configurations with lower bandwidth (the diamonds and triangles) but nominal 125 msec of time delay all had flight path bandwidths below the Level 1 limit, and hence are predicted susceptible to PIO. Note that the pitch sensitivity of the configurations represented by the triangles may have been high for their pitch dynamics, possibly the cause of the increased PIO susceptibility of these configurations.

All configurations with τ_P greater than 0.15 sec are predicted "Susceptible to PIO", and these tendencies were observed during the evaluations.

However, the criterion does not account for degrees of PIO susceptibility, as does the proposed criterion based on CAP parameters. This could be addressed by the inclusion of a diagonal line in the "Susceptible to PIO" region, approximately equidistant from the existing and proposed upper Level 2 limit on the flying qualities requirement (the plot on the left).

PHANTOM WORKS

Stability, Control & Flying Qualities

Criteria for Category I PIOs of Transports Based on Equivalent Systems and Bandwidth

Conclusions

- Level 1 / 2 CAP boundary could be raised to 0.3
- There is a multi-parameter correlation between CAP and time delay
- This same correlation is reflected in PIO tendencies
- PIO boundaries were proposed based upon LOES parameters
- Level 2 / 3 pitch Bandwidth boundary could be relaxed
- The data supports the proposed Bandwidth / PIO criterion

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Stability, Control & Flying Qualities

Criteria for Category I PIOs of Transports Based on Equivalent Systems and Bandwidth

Video of TIFS Landing

- Ground View
- Pilot View
- Configuration:
  - Angle-of-attack response-type
  - $n/\alpha = 3.9$ g/rad
  - $\omega'_{sp} = 0.3$ rad/sec
  - $T_{\theta} = 0.125$ sec

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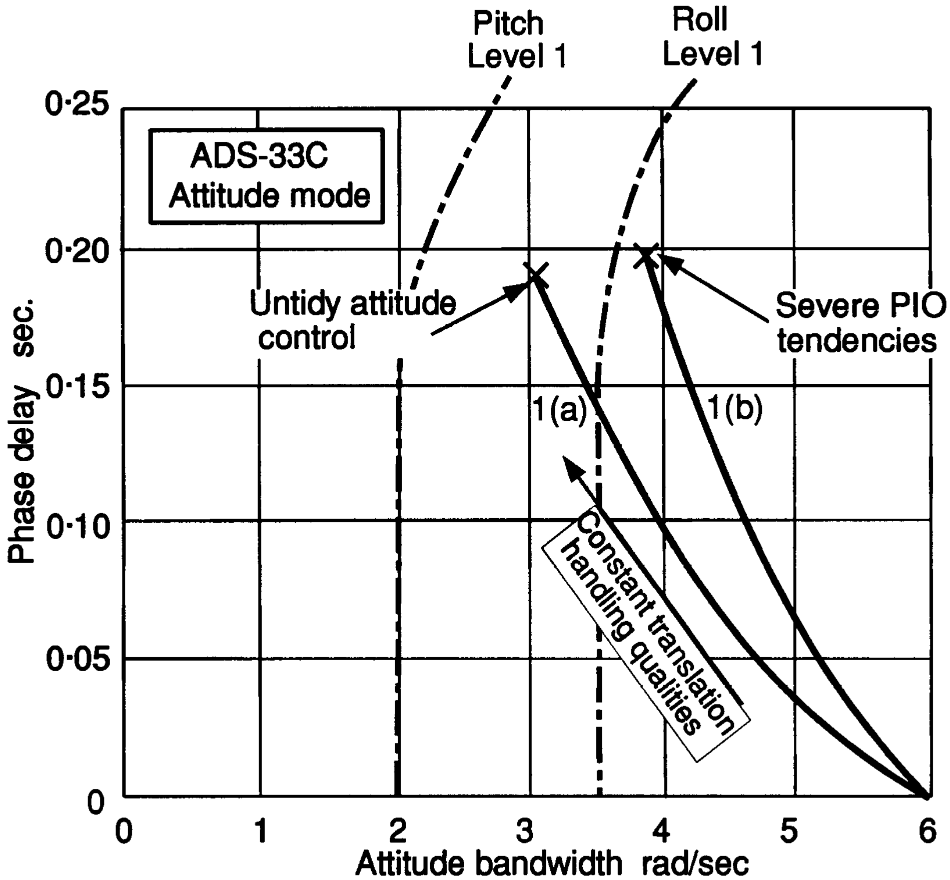
Designing to Prevent PIO

John C. Gibson
Consultant,
British Aerospace

Safety-related PIO

is like the Sword of Damocles, that may:

- break the hair and fall on you if you ignore it,
- but it can also act as a constant reminder if you act to chain it safely to the ceiling.
- Which one it is depends on you, the designer



1(a) has critical damping and low PIO gain, with translation control qualities that remain constant as bandwidth reduces and phase delay increases, while the attitude control becomes untidy.

1(b) has Level 1 damping (0·5), phase delay and bandwidth to ADS-33C, but degrades to dangerous PIO due to high PIO gain and motion coupling as phase delay increases.

Figure 1 Generic ASTOVL research:
Lateral translation handling in roll attitude mode

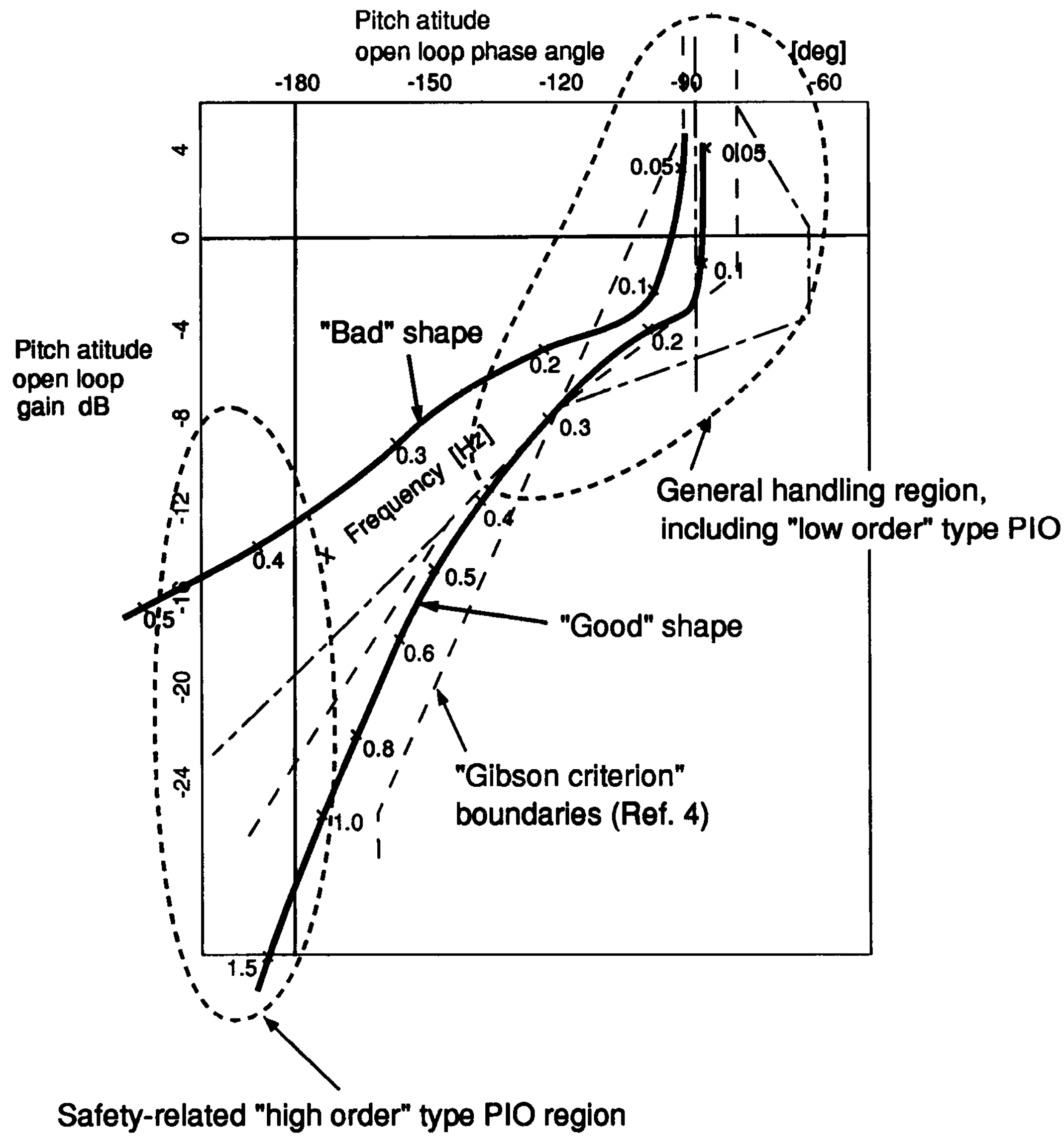
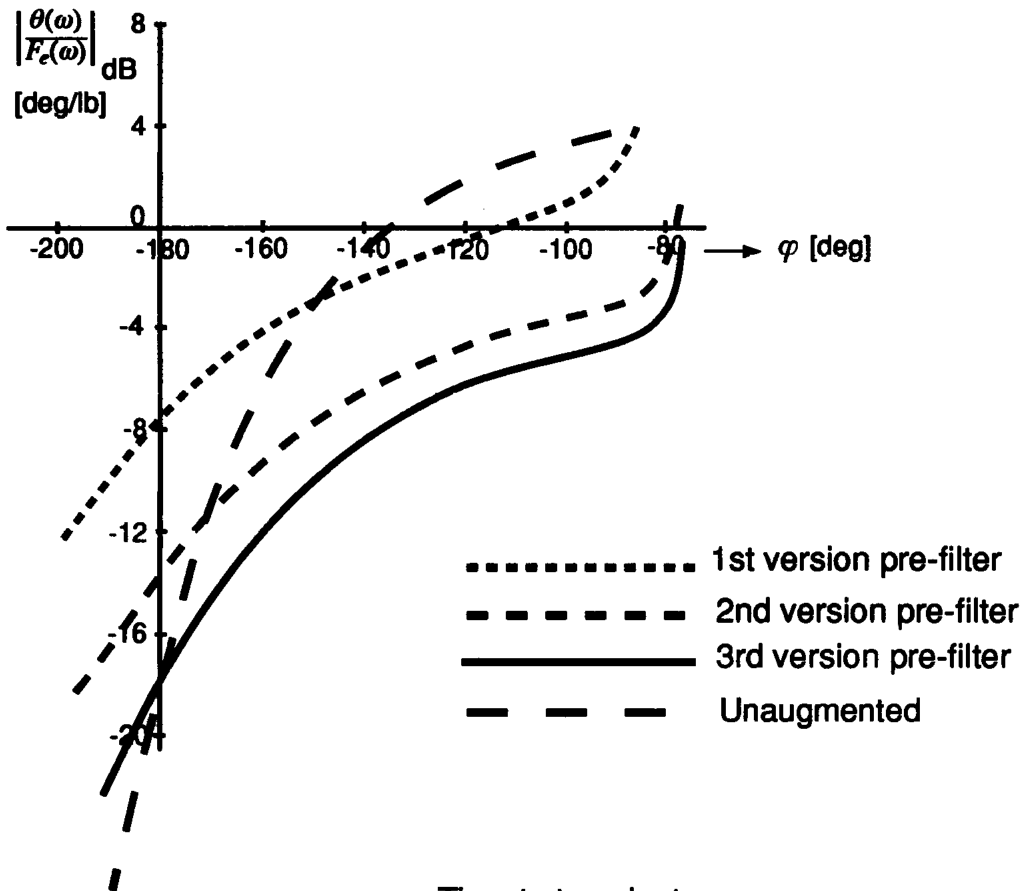


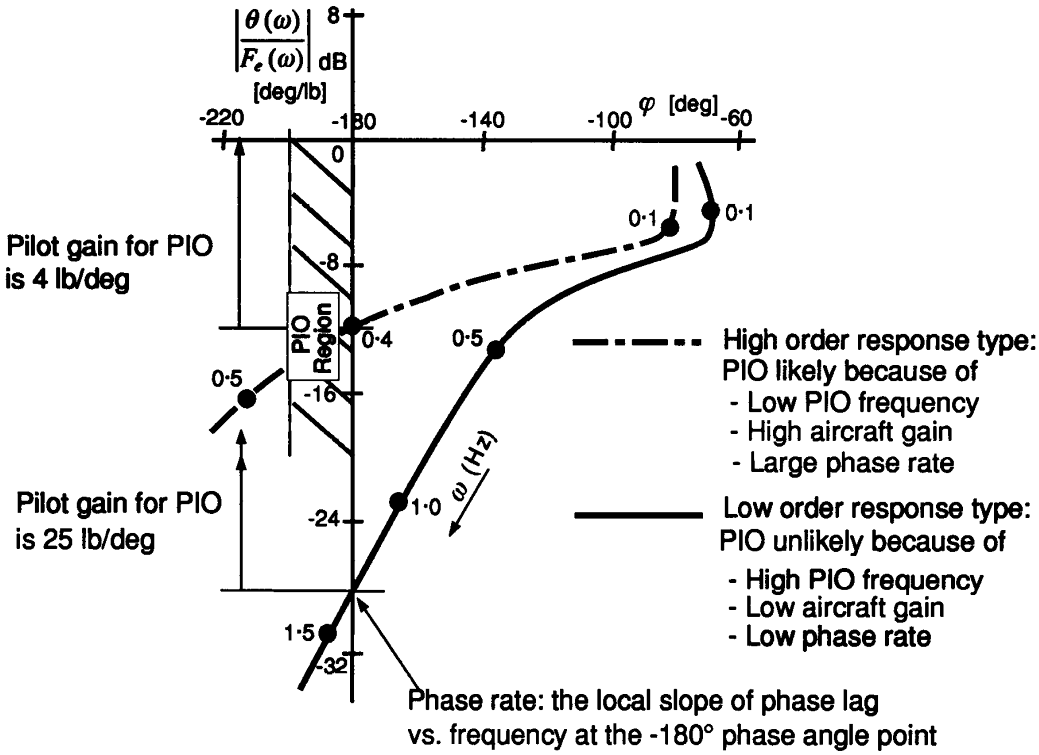
Figure 2 Frequency response qualities illustrated by non-parametric shape



Version	$\omega_{(-120)}$ Hz	$\omega_{(-180)}$ Hz	$t_{\dot{q}}$ sec	Pre-filter characteristics
	Bandwidth	PIO frequency	Time to transient acceleration peak	
1st	0·245	0·43	0·35	(1 + 0·157s)/(1 + 0·47s)
2nd	0·245	0·455	0·3	(1 + 0·133s)/(1 + 0·454s)(1 + 0·0625s)
3rd	0·26	0·535	0·22	(1·0)
Unaug.	0·145	0·44	0·12	(1·0)

Figure 3 Tornado pitch attitude responses at landing: solution to PIO by development of the command pre-filter.

The unaugmented and third version pre-filtered dynamics are PIO-free.



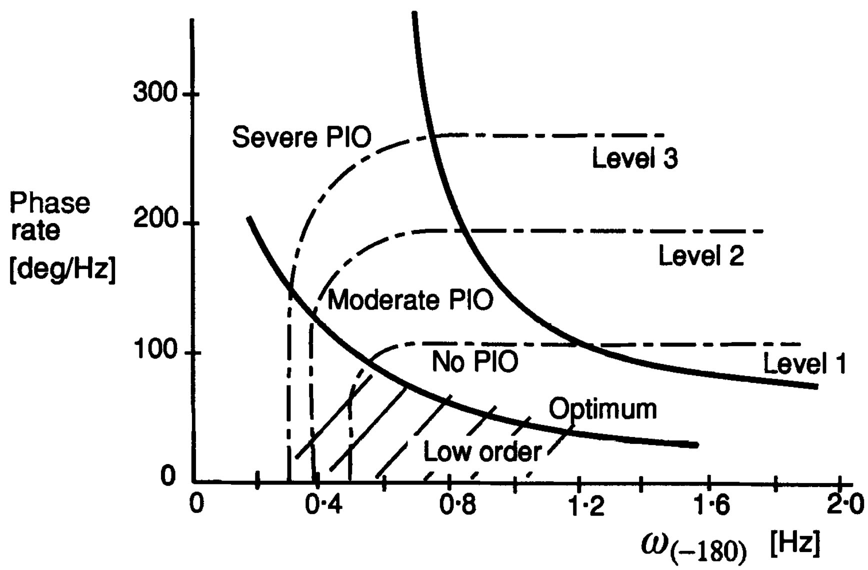
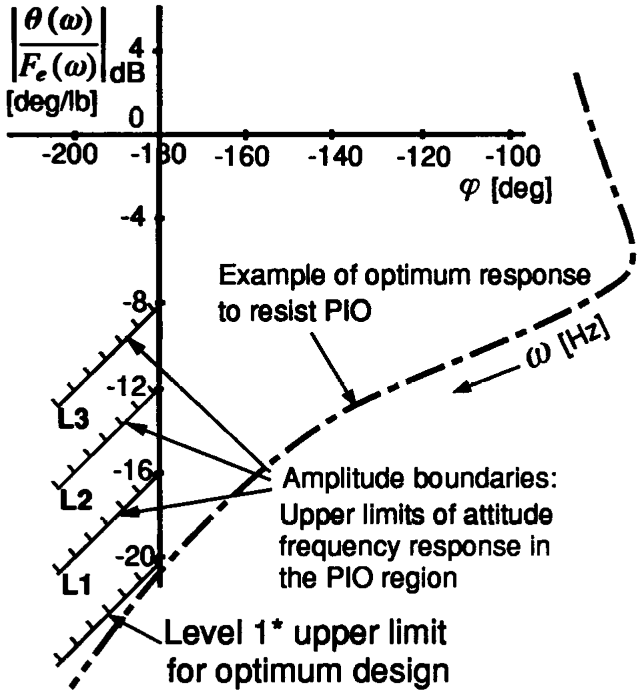
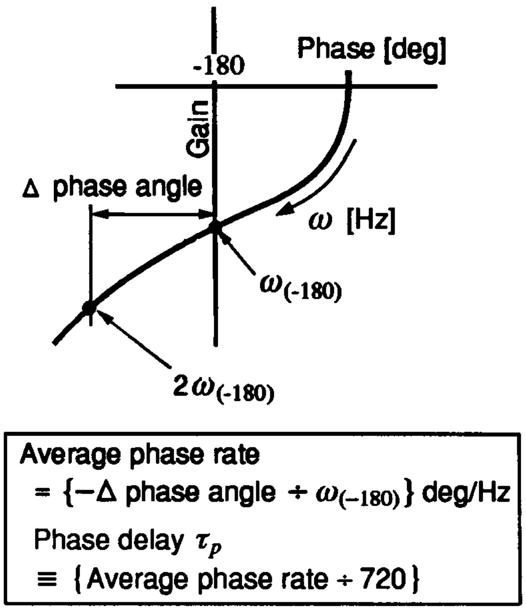


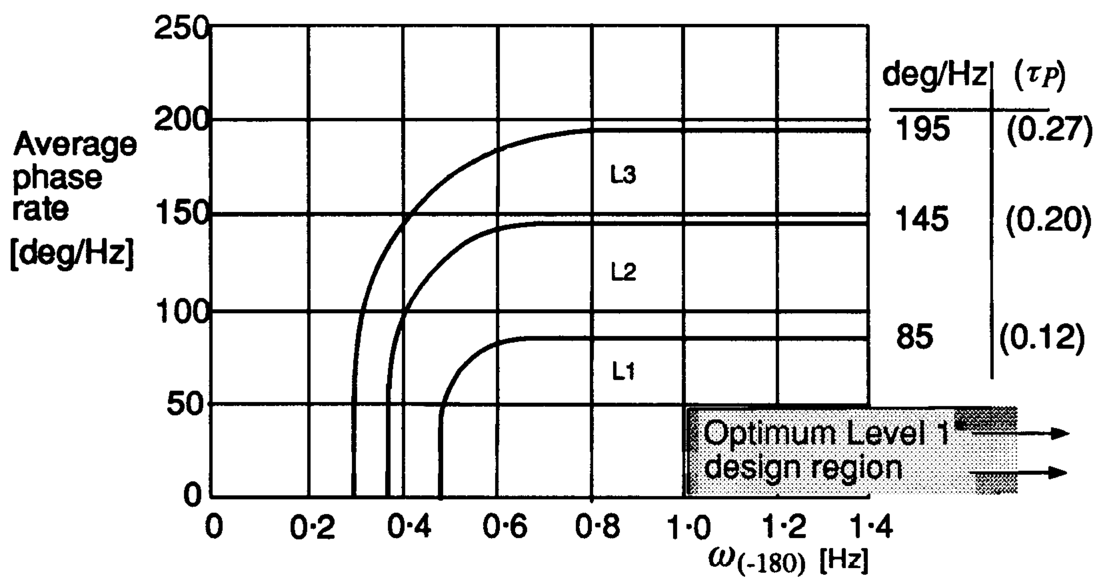
Figure 4 PIO tendency indicators and design guidelines derived from LAHOS etc.



(a) PIO gain limit criterion



(b) Definition of average phase rate



(c) Phase rate and frequency criterion

Figure 5 Final development of PIO criteria (1993)

1. Level 1, 2 and 3 boundaries represent historical data.
2. Undesirable residual high order characteristics exist within the Level 1 region near the low frequency boundary limit.
3. Best design practice for freedom from linear high order PIO requires the more stringent Level 1* gain, phase rate and frequency limits.

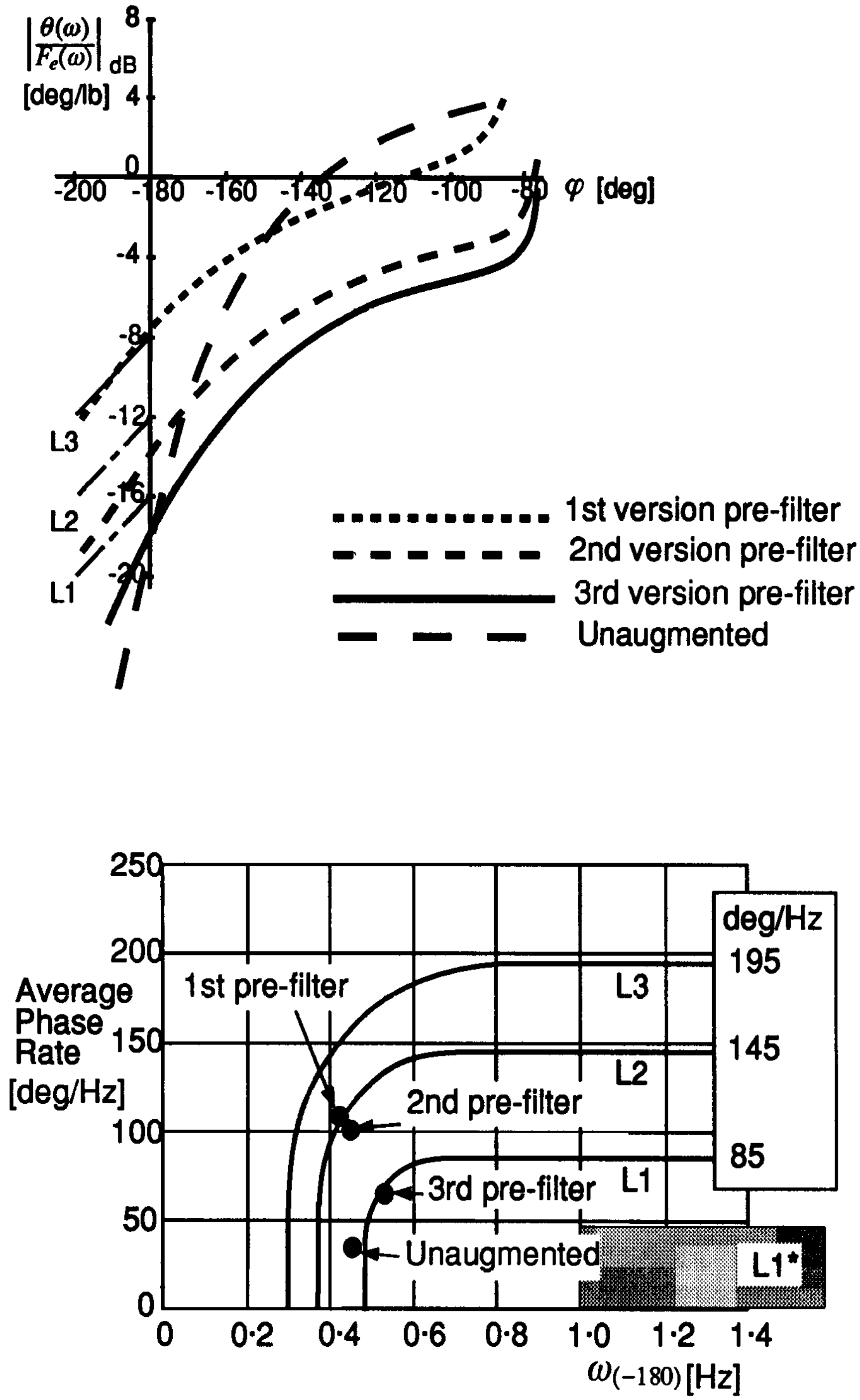


Figure 6 Tornado viewed in retrospect against author's later criteria

Note: although the 3rd pre-filter just satisfies the criterion and has prevented PIO for 20 years, it would not have been accepted as a new design by subsequent criteria.

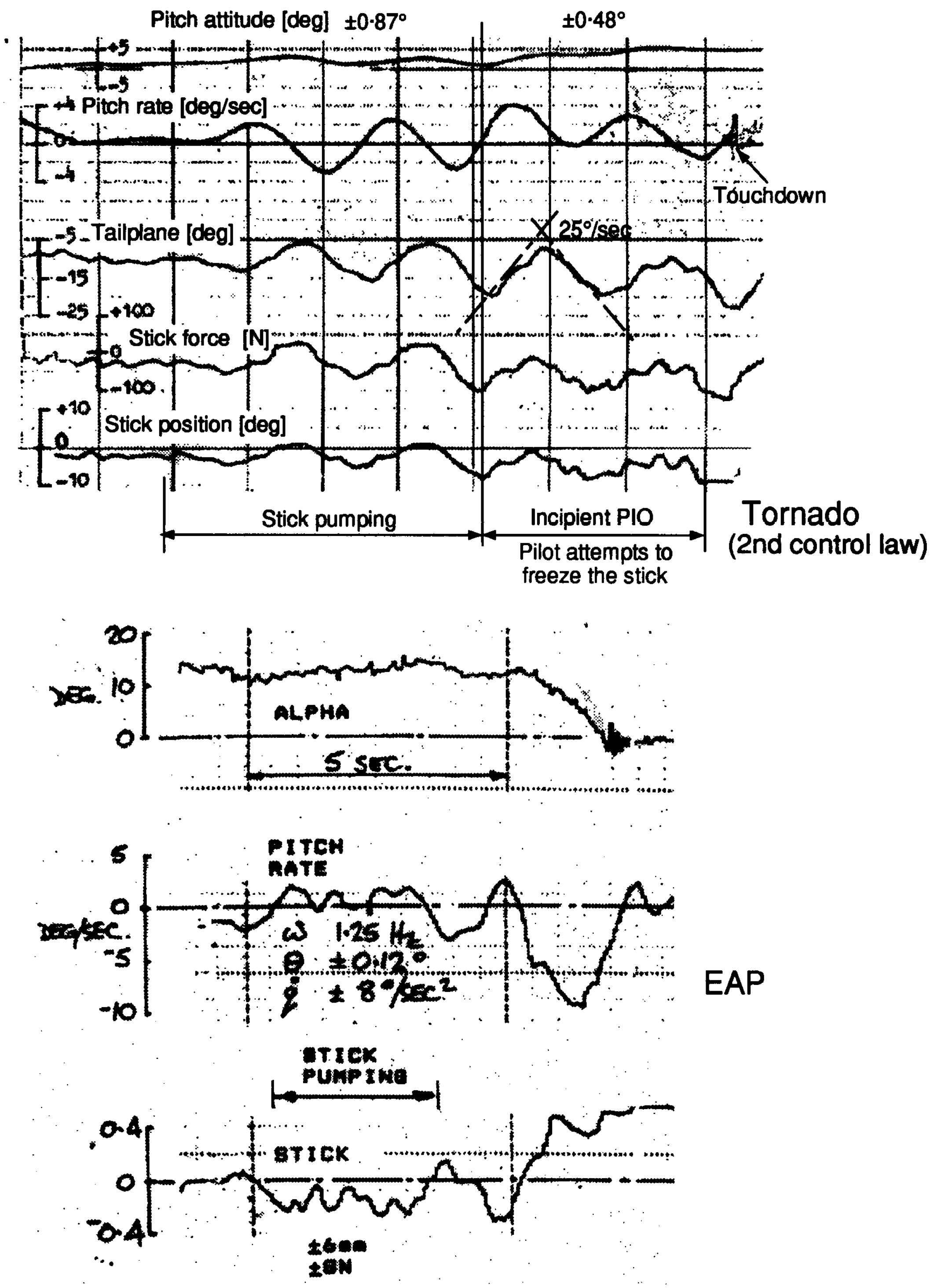


Figure 7 Effect of design process on stick pumping and associated PIO resistance

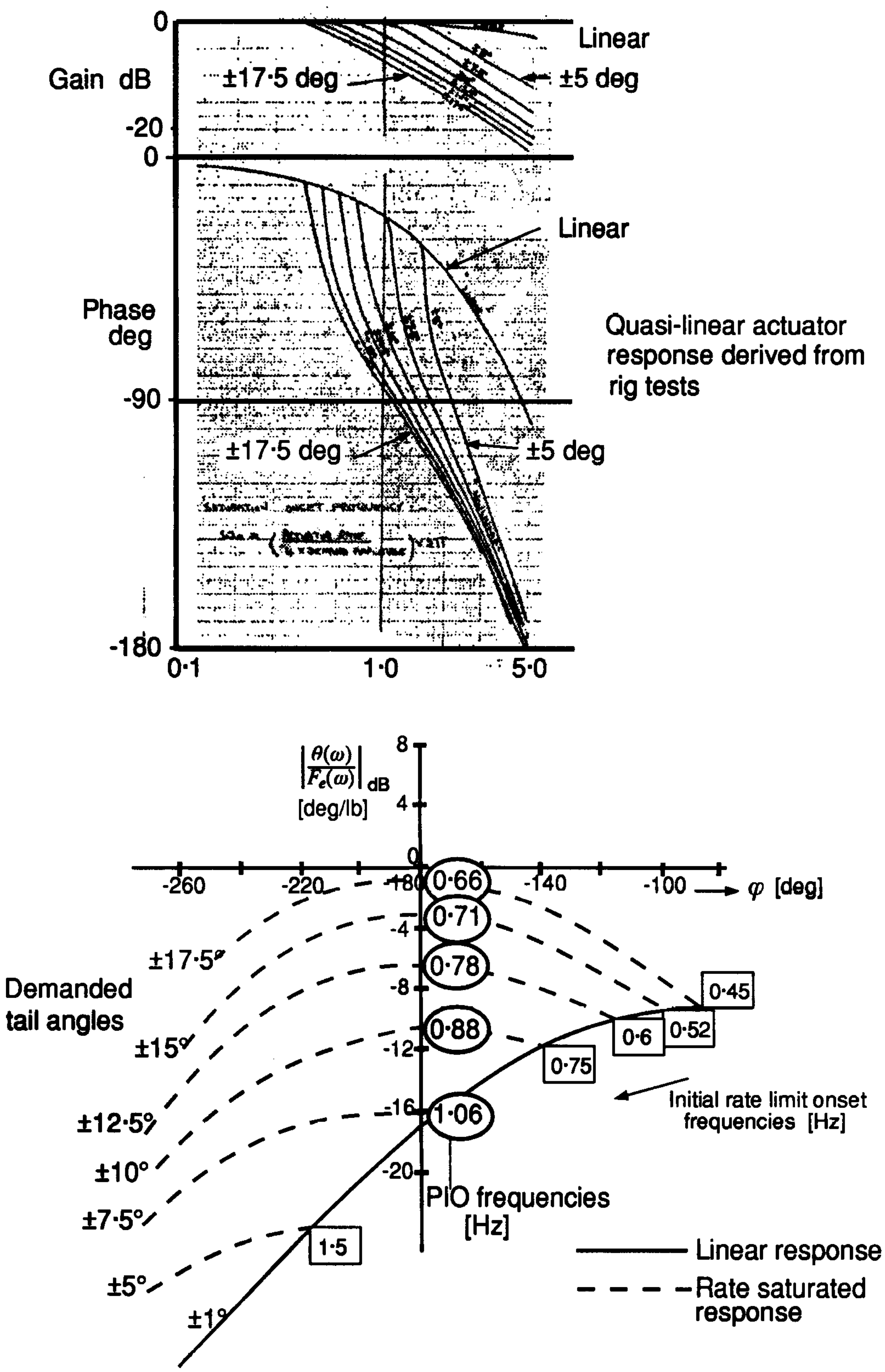
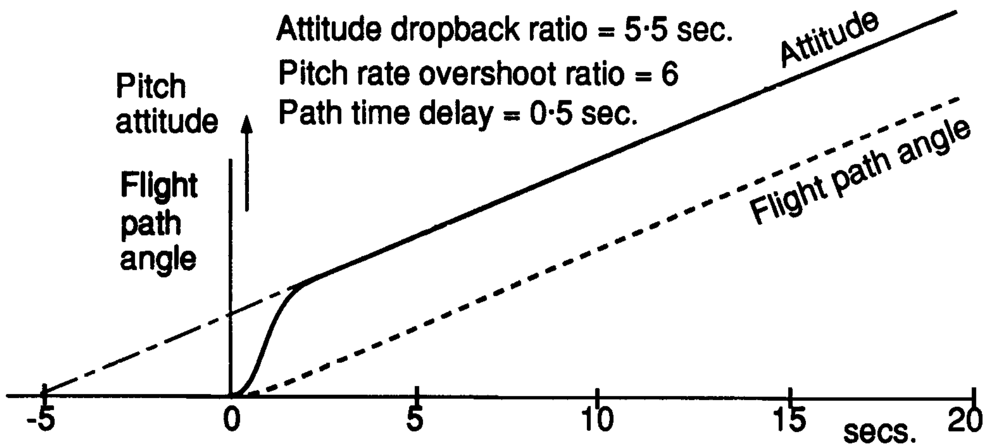
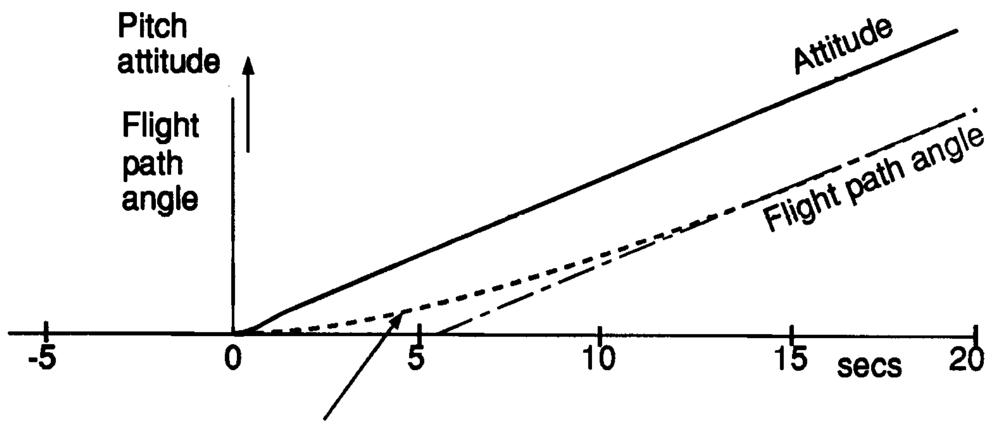


Figure 8 Significant non-linear actuation effects on PIO characteristics



Nominal YF-12 time response
at Mach 3 cruise



Short period roughly approximated by:

$\omega_{sp} = 0{\cdot}5$ rad/sec

$\zeta_{sp} = 1{\cdot}3$

Path delay = 5·2 sec.

$$\text{YF-12 with pre-filter} = \frac{1 + 0{\cdot}8s}{1 + 5{\cdot}5s}$$

Figure 9 Sluggish PIO-prone flight path response caused by inappropriate pitch attitude optimisation

Session II

Replicating HAVE PIO on the NASA Ames VMS

Jeffery Schroeder
NASA Ames Research Center

Outline

- Introduction
- Experiment description
- Results
- Known simulation/flight disparities
- Conclusions

Introduction

- Ground-based simulation has not had much success in predicting PIOs
- National Research Council recommended high priority be given to validating simulation
- Previous flight-test study (HAVE PIO) offers a set of pitch data for validation

Introduction

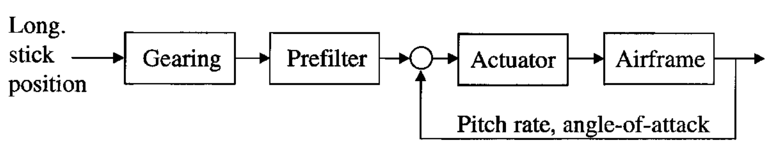
- Wright Laboratory replicated in-flight study using two fixed-base simulators
- Purpose of this study:
  - Determine if the amount of platform motion affects ability to replicate in-flight results

Experiment description

- Math model
- Task
- Visual system
- Motion configurations
- Safety pilot and miscellany

Experiment description

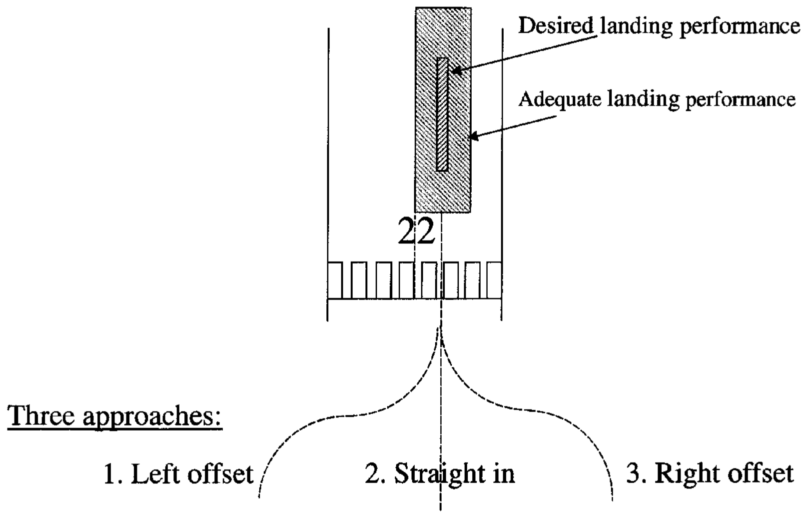
Math model



- NT-33 airframe simulated w/ stability derivs.
- 18 sets of pitch dynamics

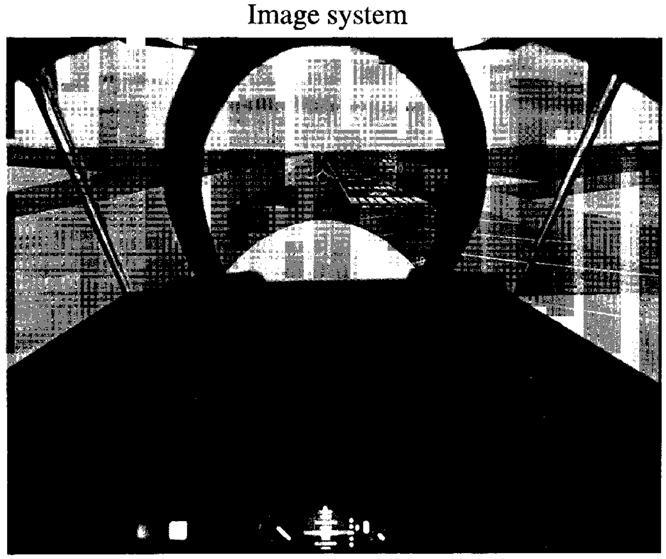
Experiment description

Task



Experiment description

Image system

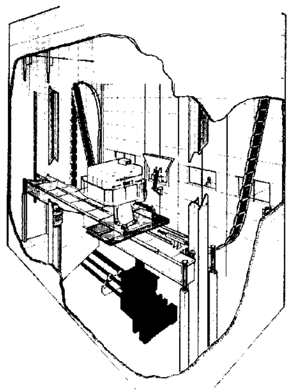


Experiment description

Motion configurations

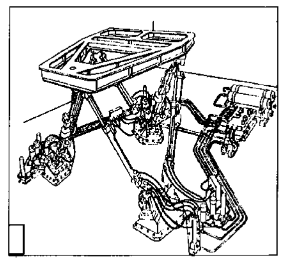
- Vertical Motion Simulator used to simulate all motion configurations

Vertical Motion Simulator displacements



Classical motion drive logic

Typical hexapod displacements (5 ft stroke)



Coordinated adaptive motion drive logic

No motion

Experiment description

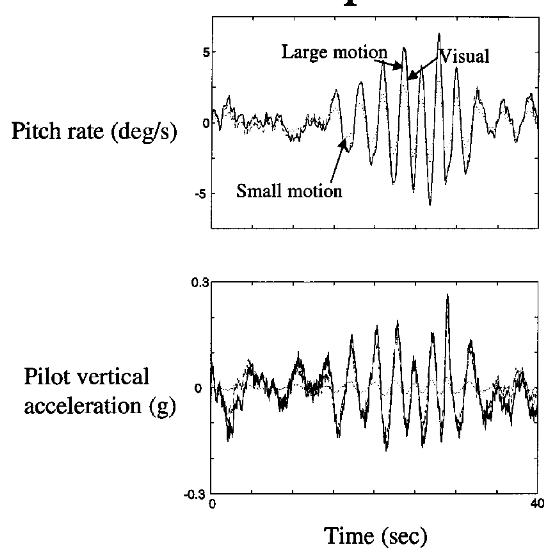
Safety pilot and miscellany

- Automated safety pilot assumed command if situation deemed hazardous
  - Nosegear sink rate > 8 ft/sec when below 12 ft
- Stick ergonomics and force-feel closely matched aircraft
- Five test pilots (3 NASA, 1 FAA, 1 Boeing) flew all combinations of motion and aircraft configurations (randomized)

Results

- Example PIO
- Handling qualities ratings
- Pilot confidence ratings
- PIO ratings
- Touchdown velocities

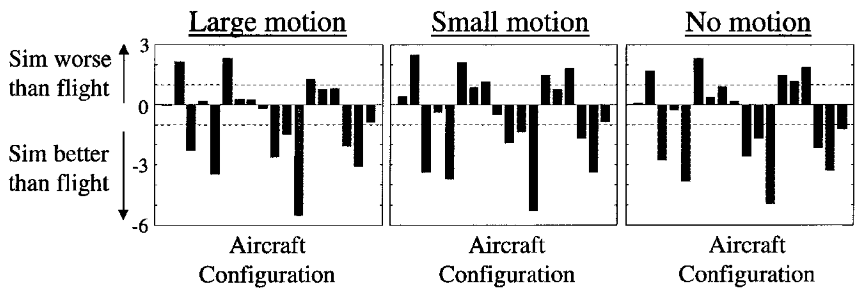
Example PIO



Large motion satisfactorily simulates pilot normal acceleration

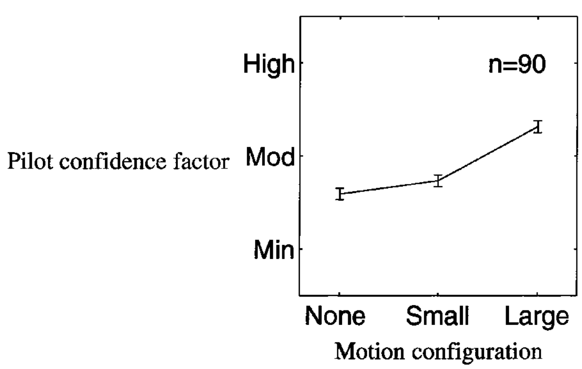
Handling qualities ratings

Simulation versus flight



Large motion had more ratings within +/- 1 of flight rating

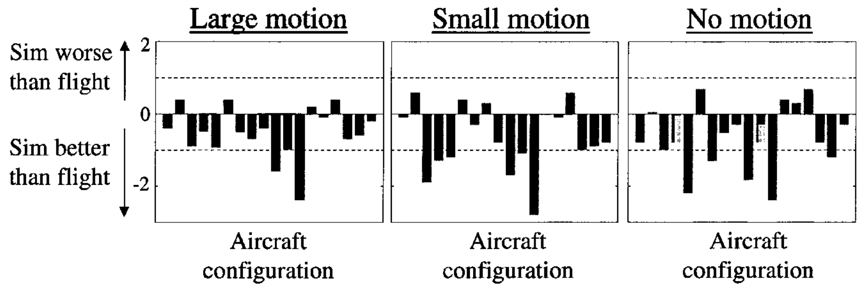
Pilot confidence factors



More confidence in rating with more motion

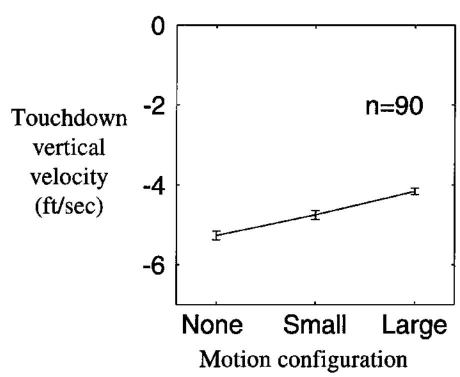
PIO ratings

Simulation versus flight



Large motion had more ratings within +/- 1 of flight rating

Touchdown velocities



Large motion allowed better touchdown sink rate control

Known simulation/flight disparities

Likely top 5

- Stress-induced environment
- Visual content
- Different evaluation pilots
- Simple automatic versus real safety pilot
- Field-of-view

Conclusions

- With large motion:
  - handling qualities ratings correlated best with flight
  - higher pilot confidence ratings achieved
  - PIO ratings correlated best with flight
  - lower touchdown velocities resulted
- Only large motion provided high fidelity vertical motion cues
- List of disparities between simulation and flight suggests future work

Replicating HAVE PIO on Air Force Simulators

Ba T. Nguyen, Air Force Research Laboratory

(Report Number 6 is not available for printing at this time)

PREDICTION OF LONGITUDINAL PILOT-INDUCED OSCILLATIONS USING A LOW ORDER EQUIVALENT SYSTEM APPROACH.

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PHANTOM WORKS

Abstract

A study was undertaken to determine whether longitudinal low order equivalent system parameters could be used to predict pilot-induced oscillations (PIOs), also known as adverse aircraft-pilot coupling (APC), for high order aircraft pitch dynamics. The study was confined to linear dynamic models, and therefore to Category I PIOs. Variable stability aircraft results were used from three data sources simulating fighter up-and-away maneuvering, fighter touchdown, and large transport touchdown. The equivalent system parameters (alone or in combination) from the current US Military Standard correlated well with incipient or developed PIOs. Excessive equivalent time delay was by far the most frequent cause of PIO, and a few cases were explained by low short period damping, low short period frequency and low maneuvering stick force gradient. A high-gain asymptote parameter offered some additional insight into pilot loop closures with large delays.

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Questions

- Can LOES parameters predict PIO?
- If LOES parameters are good, no PIO?
- If LOES parameters are bad, can get PIO?
- Do we need dedicated criteria instead?

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<u>PIO Prediction using equivalent system criteria</u>

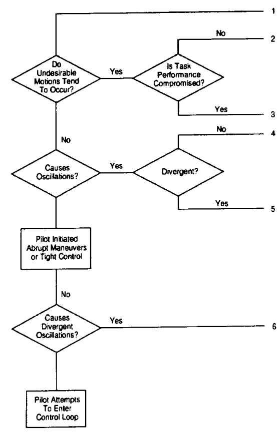
In addition, we would ideally like to answer the questions:

> .If the equivalent system parameters were good compared with the equivalent system criteria, did the pilots find no PIO tendency?
>
> .When the pilots experienced a PIO, did one or more equivalent system parameters predict a PIO?
>
> .Also, if it is difficult to obtain a match for a configuration, can this also suggest PIO susceptibility?

We were able to answer all these questions to varying degrees.

PIO Rating (PIOR) Scale

DESCRIPTION	RATING
No tendency for pilot to induce undesirable oscillations.	1
Undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.	2
Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort.	3
Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.	4
Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open loop by releasing or freezing the stick.	5
Disturbance of normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing the stick.	6



PIO ratings awarded by the pilots aided this study.

Three data sources

- Neal-Smith
- LAHOS
- GLT

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Correlation database

Three data sources were utilized. All were from in-flight simulations. Reference 6, Neal and Smith's study, examined up-and-away dynamics of fighter aircraft. Reference 10, the so-called LAHOS study, considered fighter dynamics in the landing approach. The Generic Large Transport (GLT) study of Reference 11 was for landing and touchdown dynamics of very large (approximately 1-million-pound) transports. In these data bases, the pilot ratings and comments were used to separate the configurations into those without PIO tendencies, those with incipient PIOs, and those with actual PIOs.

(for Reference definition, see the last two charts, or AIAA Paper 99-4008,'Prediction of Longitudinal Pilot-Induced Oscillations using a Low Order Equivalent System Approach', John Hodgkinson and Paul T. Glessner, The Boeing Company, Phantom Works, Advanced Transports and Tankers, Long Beach, California, and David G. Mitchell, Hoh Aeronautics, Inc., Lomita, California).

LOES form for pitch rate control

$$K_\theta \frac{(s+L_\alpha)e^{-\tau s}}{[s^2+2\varsigma_{sp}\omega_{n_{sp}}s+\omega_{n_{sp}}{}^2]}$$

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The accepted method for determining the longitudinal short period equivalent system is to match the pitch and normal load factor dynamics (at the instantaneous center of rotation) simultaneously. Similar parameters are obtained by matching the pitch rate dynamics alone with the transfer function shown in the chart, with fixed at the value for the aircraft. The transfer function numerator includes a gain; the dimensional lift curve slope of the aircraft; and a time delay. The denominator includes the short period damping and undamped natural frequency. For these pitch dynamics, good and bad values of the parameters are all defined directly or in combination by the current specification, Reference 1.

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Candidate equivalent parameters

- Time delay
- Short period frequency
- Dimensional lift curve slope
- Short period damping
- Stick force per g
- High Gain Asymptote Parameter (HGAP)

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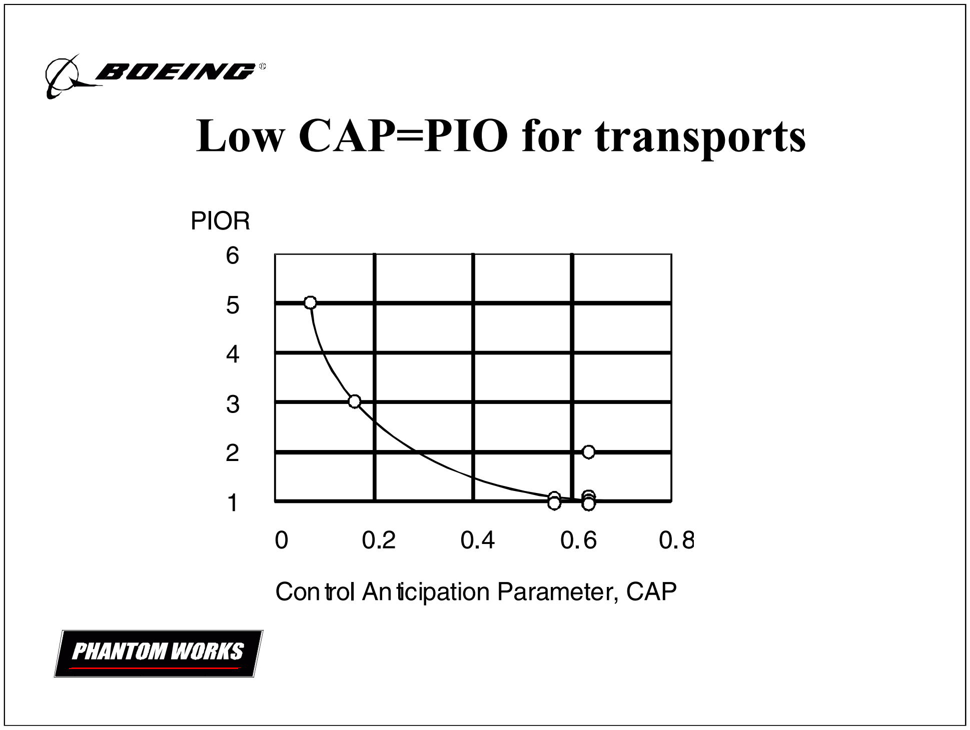
Early equivalent systems researchers quickly found that the high frequency phase lag, or rolloff, of some high order responses was greater than that which the low order forms could accommodate. Therefore a time delay term was added to the low order forms. The delay itself eventually became a criterion for handling qualities specification (see Reference 1). The High Gain Asymptote Parameter suggests that a tight pitch loop closure by the pilot could cause unstable pitch oscillations. (Ashkenas et al Reference 9). Low values of short period frequency produce sluggish dynamics and a low Control Anticipation Parameter (CAP). Low values of short period damping produce open-loop oscillations. Combined low stick force per g and low damping produces dynamic sensitivity. High steady-state sensitivity of response to stick command can produce PIO, as can combinations of rapid short period frequency with significant pitch delay. Too-abrupt (too-high) short period frequency can cause PIO. Fundamentally conventional aircraft with high mismatch, i.e., whose dynamics cannot be matched with a conventional transfer function, are unlikely to have good handling qualities. However, first, configurations with high mismatches tend to have extreme and unsatisfactory equivalent parameters, and second, if an inappropriate equivalent system form is used for an unconventional response-type (like an attitude command system), then the resulting high mismatch is just a consequence of misuse of the method.

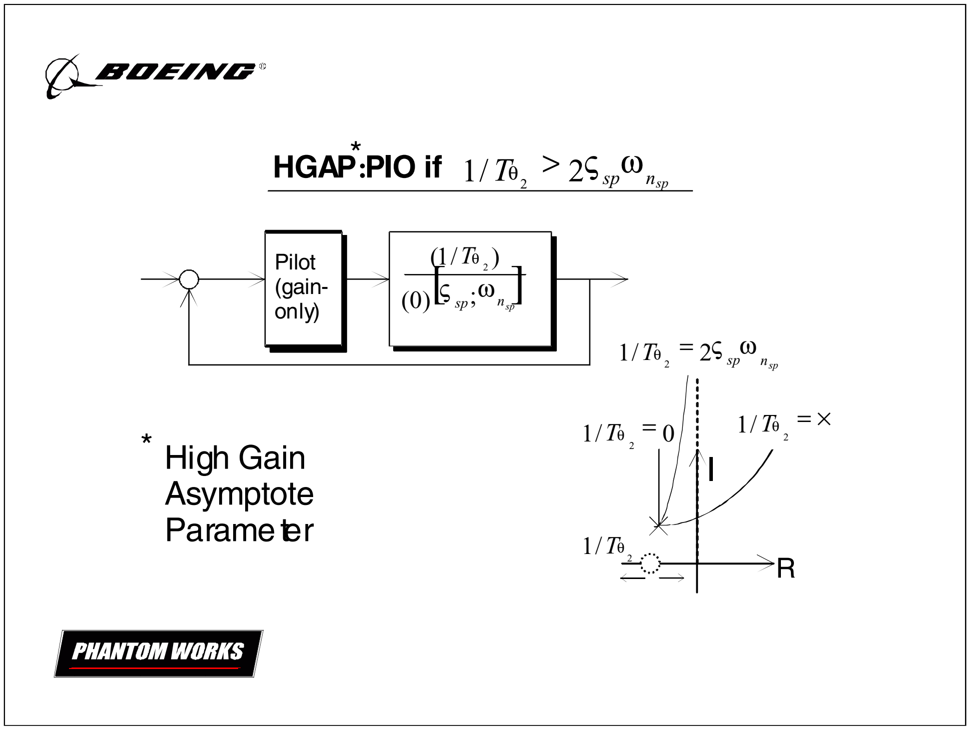


Control Anticipation parameter (CAP)

Sluggish short period frequency would be expected to correlate with PIO tendency. When all the CAP data from the experiments were plotted without regard to other parameters, a tendency to support this expectation emerged, as seen in this Table:

CAP Data Source	Apparent tendency for PIO if CAP is less than:
Neal-Smith	0.2
LAHOS	0.18
GLT	0.18

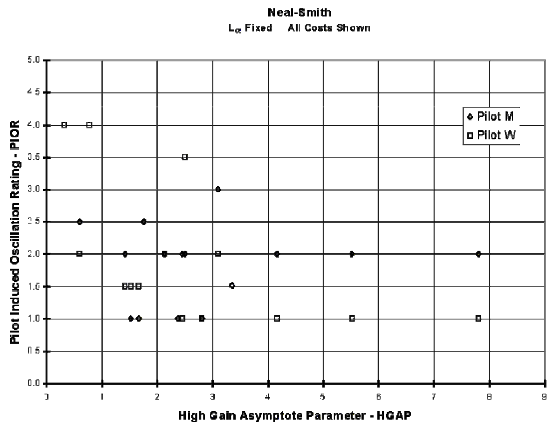
However, further examination of the data shows considerable influence of other parameters. For example, the low-CAP configurations in the Neal-Smith data generally had high equivalent delays. This is a natural consequence of how Neal and Smith added lags to fundamentally conventional dynamics to create their sluggish configurations. Lags not only add equivalent time delay at higher frequencies, but also depress the short period equivalent frequency in the mid-frequency range. When the effects of other parameters are separated from the data, we were left with only the GLT data giving a significant indication of PIO tendency due to low CAP values, as seen in the chart.



High Gain Asymptote Parameter (HGAP)

The early equivalent systems analysis of the Neal-Smith data did show a high correlation of the high gain asymptote parameter with poor ratings (Reference 2) but equivalent time delay, i.e., high frequency phase lag, dominated the PIO-prone cases. Low values of HGAP would be expected to correlate with PIO tendency. In the original theory, it was pointed out that an adverse constellation of roots for the pitch rate transfer function was unlikely for conventional aircraft, and that additional phase lags (i.e., equivalent delays) would be needed to cause PIO. Use of the 'free L-alpha' data promised to be a way of incorporating some lag into the basic root array by shifting the lead due to to artificially high frequencies. That technique also created negative values of HGAP, correlating with PIO. However, since freeing in the matching process is quite artificial, and the resulting delay values are not comparable with most studies, we do not present these data here.

Low HGAP=PIO for Neal-Smith



Plotting the HGAP (with fixed L-alpha) against PIO rating for the Neal-Smith data does show a general trend of worsening rating with smaller HGAP but for the other data bases the data did not show a clear correlation.

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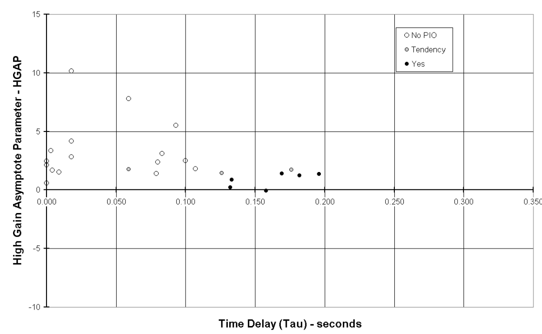
HGAP and equivalent delay... can HGAP help bad delays?



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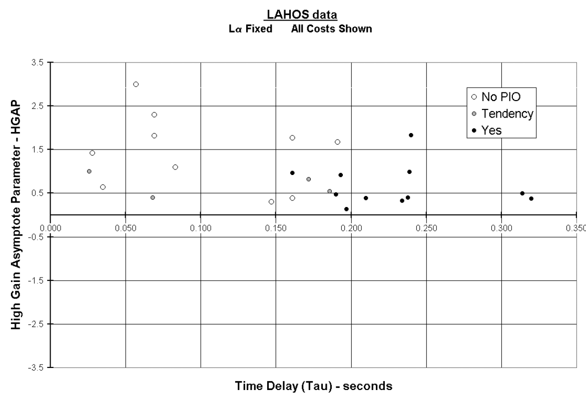
Plotting HGAP versus time delay for fixed shows that Neal and Smith’s configurations with high time delay in general also had low (theoretically bad) values of HGAP. There is a weak suggestion in the right eight data points in this Figure that the PIO tendency of configurations with high delays might be ameliorated by increasing HGAP.

Can HGAP help bad delays in LAHOS too?



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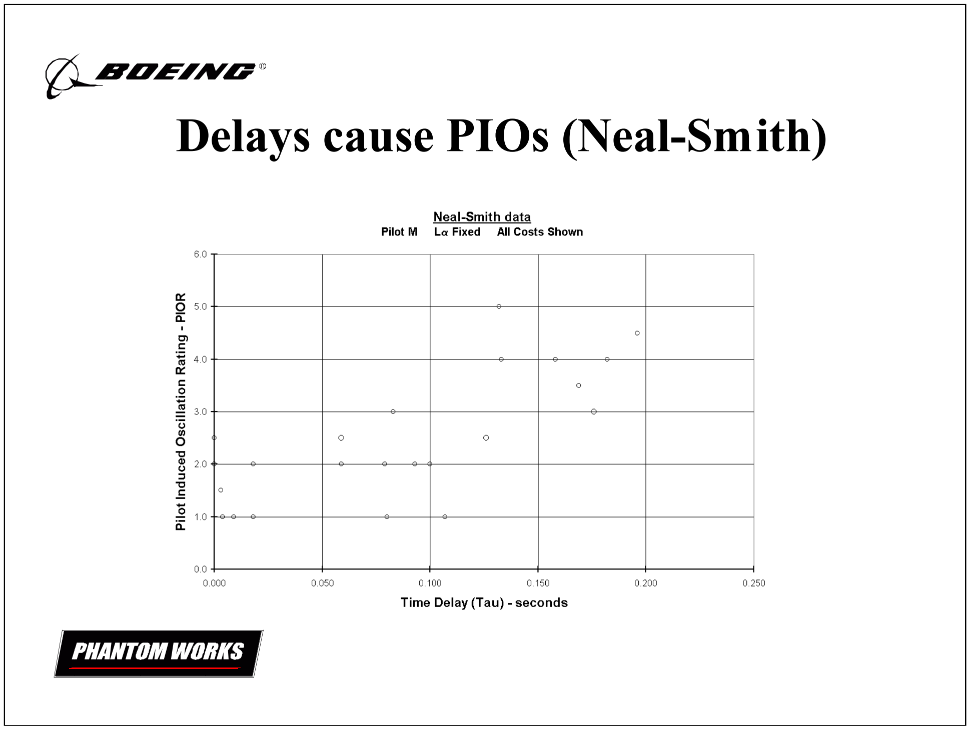
The LAHOS data also contain this weak suggestion in the region where time delay is between 0.15 and 0.2. The data are not conclusive enough to suggest an actual requirement involving HGAP. Further systematic data involving HGAP variations are needed.



Equivalent time delay

Correlation of this parameter with PIO susceptibility has previously been noted by researchers including Neal and Smith (Reference 6) and Hodgkinson et al (Reference 2). Our re-examination of the Neal-Smith data did confirm the progressive increase in PIO susceptibility with increased delay. The other data bases allowed only an indication of when tendencies towards PIO could be expected. The following Table summarizes the delay values:

Equivalent Delay

Data Source	Tendency for PIO if delay exceeds:	Definite PIO if delay exceeds:
Neal-Smith	0.12	0.18
LAHOS	0.16	-
GLT	0.25	-

Conclusions

- LOES parameters predict PIOs reliably
- Data bases mostly delay-dominated
- Low CAP for transports causes PIO
- Low Fs/n caused one PIO in Neal-Smith
- HGAP- intriguing interaction with delay?

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Conclusions

Short-period equivalent system parameters offer many clues to longitudinal PIO susceptibility. In the data examined, excessive equivalent time delay was the chief culprit. For example, in the Neal-Smith data, every configuration with a delay exceeding 0.116 seconds had a tendency to PIO. Other parameters correlating with PIO tendency included low equivalent damping ratio and low stick force per ‘g’ for the fighter configurations, and low equivalent frequency for the transport.

These results suggest that meeting the military equivalent system requirements would help to avoid PIOs.

The linear parameters used in most of the alternative PIO criteria and in the equivalent system parameters in this paper evidently address only a part of the PIO problem. Future work needs to address the roles of non-linearities and of structural dynamics.

Finally, the High Gain Asymptote Parameter (HGAP), based on linear equivalent system parameters, shows some correlation with PIOs, and there is some evidence that configurations with marginal equivalent delays may benefit from larger values of HGAP.

The work in this paper was supported by Hoh Aeronautics, Inc. under their Air Force Research Laboratory contract on PIOs, and by the Boeing Company.

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Recommendations to Improve Future PIO Simulations

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Why Important?

- Manned simulation is being relied upon ever more
- Virtual Combat Simulations
  - Used to design and set aircraft system requirements
  - Determine force mixes
- Simulation during aircraft development
  - Assess vehicle and train pilots before flight
  - Considered alternative to flight test!
- Classic use of simulation (control design tool)
  - Assess aircraft handling qualities
  - Iterate flight control design with pilot-in-loop
- Modeling and Simulation is perceived as a means to reduce costs!!

PIO Simulation Dilemma

- Historically PIOs not readily uncovered during simulation experiments
- Often found in flight test and then repeated in simulator
- Several types of PIO initiated for different reasons
  - Category I: PIOs by linear phenomena, phase loss,
    - Empirical Criteria Exist
    - Correlates to bad handling qualities
  - Category II: PIOs caused by non-linear phenomena, rate limiting position limiting, gradient breaks
    - Criteria under development
  - Category III: PIOs caused by mode switching
- PIOs generally occur when pilot is <u>high gain</u> and working hard at a <u>precision</u> task.

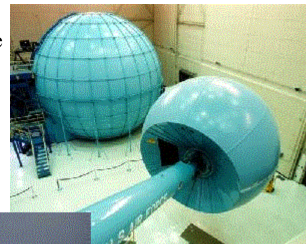
PIO Simulation Background

- AFRL/VA PIO Simulation Objectives:
  - Attempt to determine reasons why ground based simulations do not readily uncover PIOs during development
  - Use a known flight-test *truth* model to conduct comparisons to ground based implementation
  - Attempt to develop a methodology to uncover potential PIOs in aircraft more reliably via simulation
- Two truth models:
  - HAVE PIO: USAFTPS-TR-85B-S4
  - HAVE LIMITS: AFFTC-TR-97-12
- Want simulations to correlate better with flight test
  - What do we mean by correlate?

Simulation Facilities Used

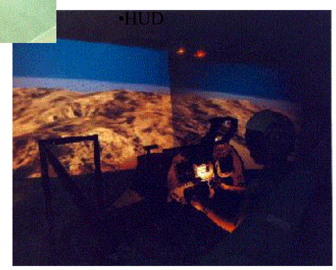
Mission Simulator 1 (MS-1)

- Fixed Base, 40Ft Dome
- McFadden Feel System
- Wrap around visuals
- HUD projected



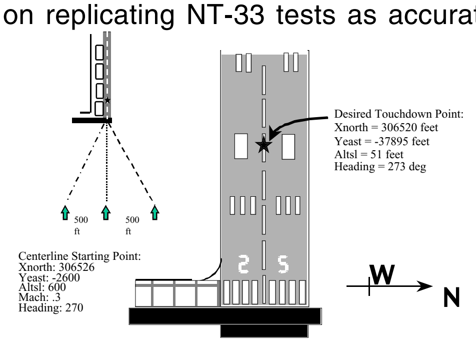
Large Amplitude Multi-Mode Aerospace Research Simulator (LAMARS)

- 5-DOF Simulator
- McFadden Feel System
- 20ft Diameter Sphere on end of 30 ft beam
- Wrap around visuals
- HUD



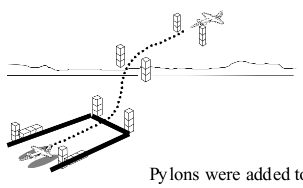
HAVE PIO Phase 1Tests

- HAVE PIO Phase 1 Tests
  - Eighteen different configurations
  - Linear sources of PIO
  - LAMARS (w/wo motion) and MS-1
  - Power approach task only
  - Priority on replicating NT-33 tests as accurately as possible

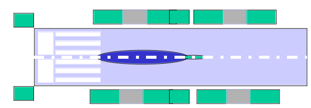


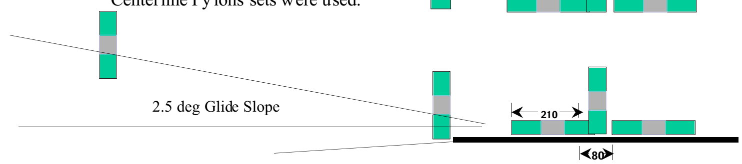
HAVE PIO Phase 2 Test

HAVE PIO Phase 2 Tests
- •MS-1
- •Power approach only
- •Assessed simulation tweaks
  - •Stick Gain
  - •Time delay
  - •Winds/Turb/Gusts
  - •Pylons



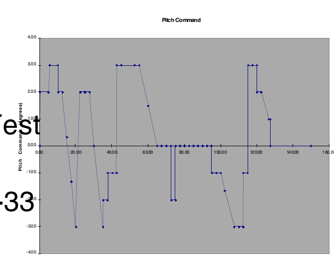
Pylons were added to the landing task to force pilots to fly a particular path and to hi-light the touchdown point. Left, Right, and Centerline Pylons sets were used.

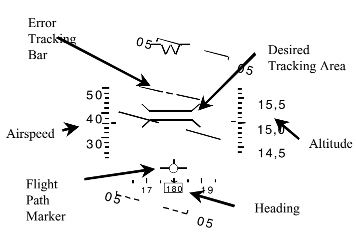


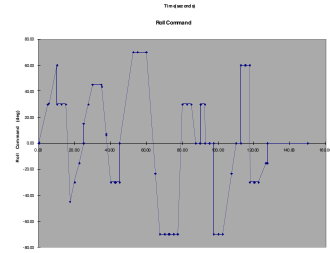


HAVE LIMITS Tests

- HAVE LIMITS Tests
  - LAMARS with motion (retune)
  - SOS and Calspan Discrete task
  - Attempt to correlate with NT-33 Test
  - Core of an expanded database
  - Changed HUD Symbology from NT-33







Results

- **HAVE PIO**
  - **Able to generate Category I PIOs in simulation**
  - **Desired correlation between flight and simulator per configuration not achieved**
  - **Data trend: good was good, but bad was not as bad**
- **HAVE LIMITS**
  - **Initial tests uncovered problems with model replication between what occurred in-flight and what was integrated on simulator**
  - **Category II PIOs replicated in simulation**
- ***Wanted direct correlation with flight test for each configuration or predictable variation across Cooper-Harper and PIO Rating Scales***

Reason for Differences

- Fundamental difference between handling qualities evaluations and PIO experiment
  - Evaluating a configuration versus searching for defects
- Pilot variability even a larger factor in PIO experiments
  - Large variations not unusual
  - 3 Pilots do not a make a sufficient sample space
  - Pilot technique
- Briefing Techniques
  - This has an effect: Reviewing PIO charts, definitions
- Task Definitions
  - Already difficult to match reality
- It's a simulation!!!!!!!!

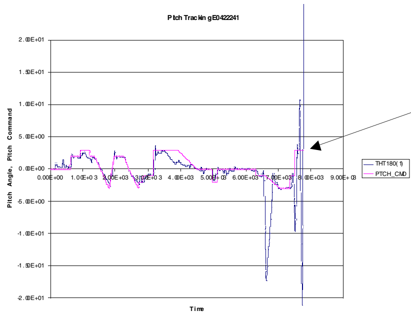
PIO Testing

- Hypothesis: Fundamentally different from standard handling qualities testing
- During HQ testing pilots are rating the configuration as is, not actively looking for deficiency
  - If we run into PIO great, if not, no PIO
  - This does not imply configuration is not PIO proof
- PIO requires an active search
- Test matrix and task development require much more attention and care
- Need real-time measure of pilot effectiveness during task to keep honest (RMS , Touchdown dispersions)

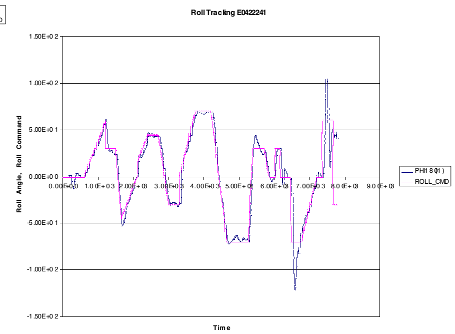
Task Generation

- PIO Testing requires closed loop high gain tasks that stress pilot/vehicle system
- Approach Task Too Open Loop
  - Suggest use of pylons, ILS needles
  - Measure pilot performance along path
  - If pilot doesn't land is that a CH 10???!!!
- Discrete Tracking Task
  - Works well in simulator
  - Pilots game system so variations must be used to avoid learning
  - Requires Tuning, we found pilots could trip into PIOs especially ir one region!
- Remember: It's a simulation

Tracking Task



Gotcha Region



Pilot had rated this pitch configuration (2DUR30) in earlier runs as a CH-2 PIOR-1. During this run a rate limited roll was added to increase workload.

Pilots

- Natural variability puts pressure on other parts of PIO te
  - Need more than 3 pilots, but not just for statistics
  - High/Low Gain, Golden Arm, The guy who hates simulators
- Shouldn’t fly more than an hour !
  - Fatigued pilots good for PIO generation but bad evaluators
  - Fresh pilots make good evaluators but poor PIO generators
  - When pilots refer more and more to previous runs, break!!!
- Need to keep aggressive by any means necessary
  - RMS feedback worked well, but when do we give to pilot?
- Need to reset pilots often
  - Good->Bad, follow really bad config with a good config

Pilot Briefing

- Critical to success of any test.
  - Not all Test Pilots have seen a PIO
- Define PIO
  - What is a bobble? What is an oscillation? Overshoot?
  - Does backing out of loop imply PIO and what to do?
- Define tolerable/intolerable workloads and define adequate and desired.
  - Some pilots definitely have a distinct definition of these.
- Pilot ratings in a simulator
  - Level 1 ratings reserved, psychological block
  - Some pilots won't even give a CH-10!!!!
  - Pilot can crash in a plane but not in a simulator

Simulation Motion

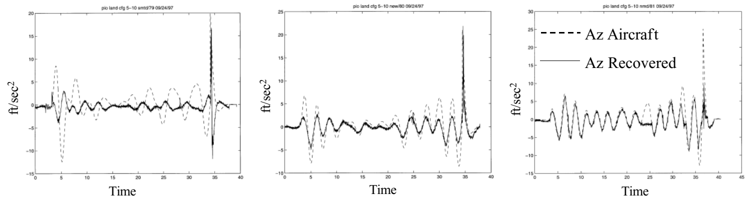
- Motion versus no-motion
  - Well tuned motion helps
  - Extra cueing to pilot, especially of AZ phasing
  - Give hint to pilot if something is not right
- Lack of motion puts pilot reliance on visual cueing
  - Hard to discern rates of descent
  - Visual detail limitations
  - During air-to-air tracking scenery isn't important anyway
- Hard to determine value due to interpilot/intrapilot variability
  - Can't really determine worth via Cooper Harper Ratings
  - Pilot comments have been extremely positive
- If good motion doesn't help does bad motion really hinder?

Motion Work

Objective: Maximize Acceleration Recovery

Use the most motion travel w/o hitting limits

Minimize False cues with proper phasing



SMTD Washout — Tuned Linear Washouts — New Non-Linear Drive

Non-Linear: Uses Fuzzy Logic Approach

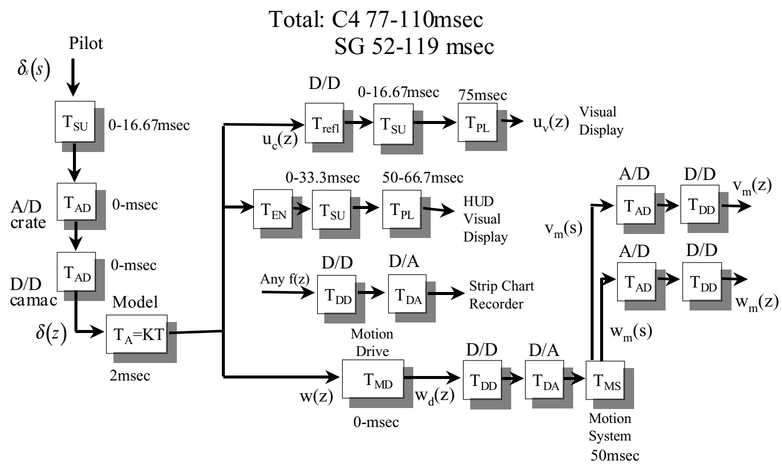
Uses Predetermined Braking and Return Profiles

Uses Human Thresholds and Indifference Levels

Wrap Up

- Simulation≠ Replication!!!!!
  - Attempting to replicate flight test results dubious effort
- PIO simulations require extra effort in other areas
  - Not asking do you like this or not?
  - Asking, did you find a problem
- The more pilots the better
- Test setup and pilot brief can do more to trash results than simulation artifacts
- Task design critical. Can only do so much to simulator
- Motion use recommended, but must be properly tuned t be of benefit

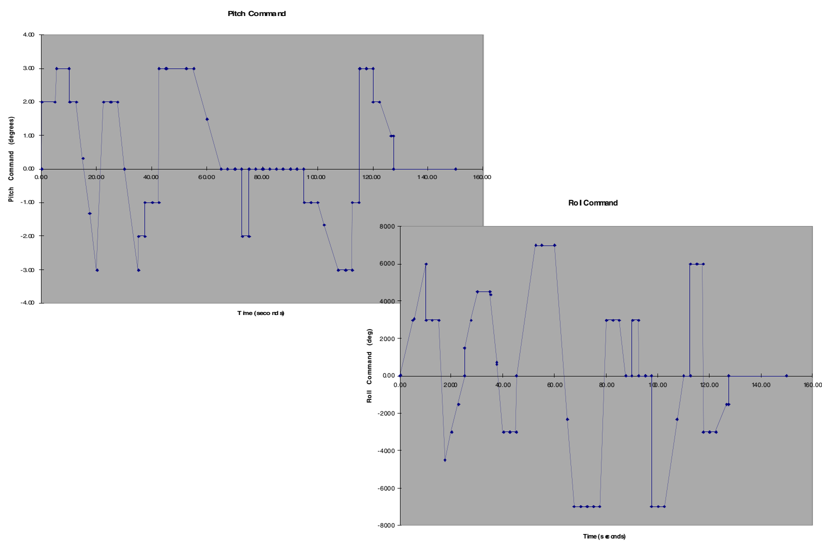
Analytical Time Delay Measurements



Measured Time Delays

- Two types of delay measurements in simulators
  - Time Domain: time to wiggle to time to response
  - Frequency Domain: Sum-of-Sines phase delay
  - LAMARS freq domain tests accomplished on motion while both freq and time measurements were done on visual
  - MS-1 only time domain tests were done on visual
- LAMARS Measured Visual System Delays
  - Compuscene transport delay: TD=88msec
  - Compuscene End-to-End: TD=108-124msec FD=72msec
  - HUD End-to-End: TD=69-153msec
- MS-1 Measured Visual System Delays Time Domain
  - Compuscene transport delay: TD=75msec
  - Compuscene End-to-End: TD=94-111msec
  - HUD End-to-End: TD=69-153msec

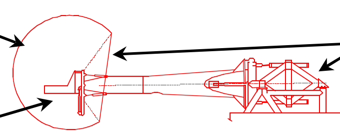
Tracking Task



Motion Work

6 Video Channels

5-DOF Cab pitch, roll, yaw, heave, and sway



Pilot Station Sensor Package:
2 Accelerometers Az, Ay
3 Rate Gyros

- Conducted parameter identification of all servo-axes.
- Developed new beam compensation terms.
- Retuned linear washout terms.
  - Used new terms during HAVE LIMIT testing
- Non-linear washout scheme developed for AZ cueing
  - Implemented tested using Capt. Chapa as test subject
  - Initial feedback good both subjective and analytical

Session III

FAA'S HISTORY WITH APC

Guy C. Thiel, FAA

FAA'S HISTORY WITH APC

- BACKGROUND
- INITITAL DEVELOPMENT OF CRITERIA
- FINAL CRITERIA & RATINGS SCALE

BACKGROUND

- **1993** - Special Certification Review
  - High Altitude Turbulence Upsets
- **1994** - Initial Draft Criteria - FBW Program
- **1995** - First Meeting of NRC Committee
- **1996** - New AC 25-7 with APC included
- **1997** - Final Release of AC with Comments

BACKGROUND

- MD-11 INCIDENTS
- FLYING QUALITY RULES
  - ONLY CLOSED LOOP
  - NO HIGH ALTITUDE TASKS

INCIDENTS

- MD-11 HIGH ALTITUDE UPSETS
- OTHER INCIDENTS
- CAUSES

  Basic Handling Qualities ??

  Lack of Training

  Unusual Atmospheric Conditions

FLYING QUALITY RULES

- Normally Open Loop Tests
- Tasks are not Used in Certification
- High Altitude Flying - Autopilot

CRITERIA

- REGULATORY BASIS - FAR 25.1143

- A) The Aircraft must be safely controllable and maneuverable throughout the flight envelope.

- B) Must be possible to make smooth transitions from one flight condition to other flight conditions without
  1) exceptonal pilot skill, alertness, or strength
  2) exceeding airplane limiting load factor

CRITERIA

- Link FAR 25.143

- Handling Qualities Rating Scales FBW Aircraft

- FAA Rating Criteria

- Develop APC/PIO Rating Scale

IMPLEMENT CRITERIA

- Use Advisory Circular Method
  - A) New Rules - 5 to 7 Yrs.
  - B) Add to Flight Test Guide (25-7)
  - C) Para. for FAR 25.143
- Add Required Maneuvers
- Tie APC Ratings to HQR Section

IMPLEMENT CRITERIA

- Issued Draft of AC 25 - 7 in Early 1996
- Basis for Certification
- Aircraft Tested - MD-11, B-777, IL-96T, A330-200, Citation X, G-5, Global Express

NEW CRITERIA

- Published AC 25 - 7 (Original Criteria)
- Train FAA Test Pilots
- Modify Original AC 25-7 Material

TRAIN TEST PILOTS

- Select First Group for Calspan Training
- Interim use of Intitial Group
- Plan for Remaining Pilots

MODIFY APC CRITERIA

- Because of Results from Past Programs
- Add Operational Maneuvers
- Require Tracking Device
- Modify APC/PIO Rating Scale

FIGURE 20-1. SAMPLE PITCH TRACKING TASK

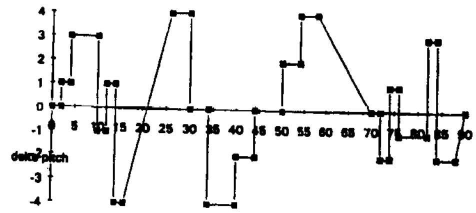


FIGURE 20-12

APC RATING CRITERIA AND COMPARISON TO MIL STANDARD

FAA HQ RATING	APC CHARACTERISTICS DESCRIPTION	MIL 1797A STANDARD PIO RATING SCALE
SAT	NO TENDENCY FOR PILOT TO INDUCE UNDESIRABLE MOTION.	1
	UNDESIRABLE MOTIONS (OVERSHOOTS) *TEND TO OCCUR* WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BY PILOT TECHNIQUE. *(NO MORE THAN MINIMAL PILOT COMPENSATION REQUIRED)*	2
ADQ	UNDESIRABLE MOTIONS (UNPREDICTABILITY OR OVER CONTROL) *EASILY INDUCED* WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BUT ONLY AT SACRIFICE TO TASK PERFORMANCE OR THROUGH *CONSIDERABLE* PILOT ATTENTION AND EFFORT. *(NO MORE THAN EXTENSIVE PILOT COMPENSATION REQUIRED)*	3
CON	*OSCILLATIONS TEND TO DEVELOP* WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. ADEQUATE PERFORMANCE IS NOT ATTAINABLE AND PILOT MUST REDUCE GAIN TO RECOVER. (PILOT CAN RECOVER BY MERELY REDUCING GAIN)	4
UNSAT	*DIVERGENT OSCILLATIONS* TEND TO DEVELOP WHEN PILOT INITIATES *ABRUPT MANEUVERS* OR ATTEMPTS TIGHT CONTROL. PILOT MUST OPEN LOOP BY RELEASING OR FREEZING THE CONTROLLER.	5
	DISTURBANCE OR *NORMAL PILOT CONTROL* MAY CAUSE DIVERGENT OSCILLATION. PILOT MUST OPEN CONTROL LOOP BY RELEASING OR FREEZING THE CONTROLLER.	6

Ratings contained in Appendix 7

__SAT = Satisfactory

__ADQ = Adequate

__CON = Controllable

UNSAT = Unsatisfactory or Failed, corrective action must be taken.

Minimum Rating, Pass/Fail Criteria Presented in Appendix 7

Flight Envelope **	NFE	OFE	LFE	NFE	OFE	LFE	NFE	OFE	LFE
Atmospheric Disturbance	Calm or Light			Moderate			Severe		
Normal to Probable Failure $< 10^{-5}$	Sat	Sat	Adq	Adq	Con	Con	Con	Con	Con
Improbable Failure 10^{-5} to 10^{-9}	Adq	Adq	Con	Con	Con	N/A	Con	N/A	N/A

Sat = Satisfactory
Adq = Adequate
Con = Controllable
N/A =Not Applicable, No Requirement

** = see Figure 6 of Appendix 7 for details of the flight envelope descriptions

NFE = Normal Flight Envelope,is associated with routine operation and/or prescribed conditions for all engine and one engine inoperative.

OFE = Operational Flight Envelope, is associated with warning onset outside the normal flight envelope.

LFE = Limit Flight Envelope, is associated with the airplane design limits or electronic flight control system protection limits.

Atmospheric Disturbance Level:

Light: Turbulence momentarily causes slight, erratic changes in altitude and/or attitude (pitch , roll and yaw). Crosswinds up to 10 knots.

Moderate:- Turbulence has greater intensity and changes in altitude and/or attitude and flight path and usually causes variations in indicated airspeed. Crosswinds up to 25 knots.

Severe:- Turbulence can cause large, abrupt deviations in altitude and/or attitude and flight path as well as large variations in indicated airspeeds. Crosswinds can be substantially larger than the minimum required crosswinds to be demonstrated.

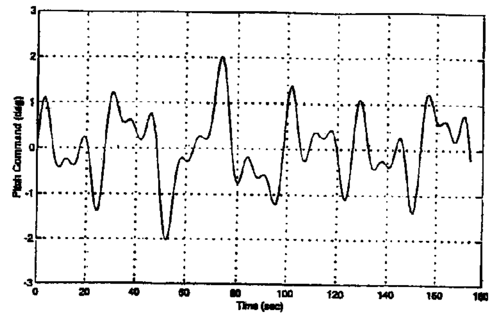
FIGURE 20-2. A-PC RATING CRITERIA AND COMPARISON TO MIL STANDARD

FAA HQ RATING	A-PC CHARACTERISTICS DESCRIPTION
SAT	NO TENDENCY FOR PILOT TO INDUCE UNDESIRABLE MOTION.
	UNDESIRABLE MOTIONS (OVERSHOOTS) TEND TO OCCUR WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BY PILOT TECHNIQUE. (NO MORE THAN MINIMAL PILOT COMPENSATION REQUIRED)
ADQ	UNDESIRABLE MOTIONS (UNPREDICTABILITY OR OVER CONTROL) EASILY INDUCED WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BUT ONLY AT SACRIFICE TO TASK PERFORMANCE OR THROUGH CONSIDERABLE PILOT ATTENTION AND EFFORT. (NO MORE THAN EXTENSIVE PILOT COMPENSATION REQUIRED)
CON	OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. ADEQUATE PERFORMANCE IS NOT ATTAINABLE AND PILOT MUST REDUCE GAIN TO RECOVER. (PILOT CAN RECOVER BY MERELY REDUCING GAIN)
UNSAT	DIVERGENT OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. PILOT MUST OPEN LOOP BY RELEASING OR FREEZING THE CONTROLLER.
	DISTURBANCE OR NORMAL PILOT CONTROL MAY CAUSE DIVERGENT OSCILLATION. PILOT MUST OPEN CONTROL LOOP BY RELEASING OR FREEZING THE CONTROLLER.

SAT = Satisfactory
ADQ = Adequate
CON = Controllable
UNSAT = Unsatisfactory or Failed

CALSPAN
An Operation of Veridian

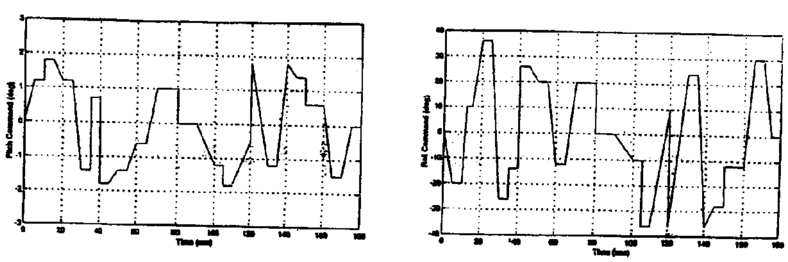
Tools for the Evaluation Pilots



Sum of Sines Tracking Task
(similar in roll)

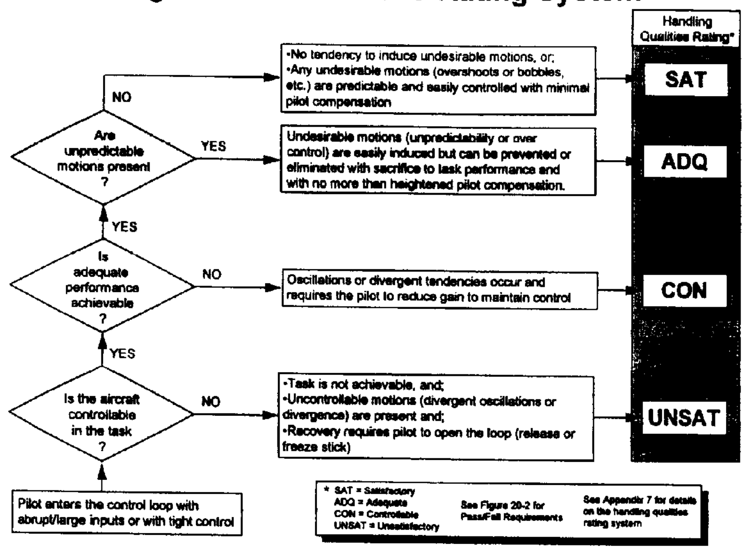
CALSPAN
An Operation of Veridian

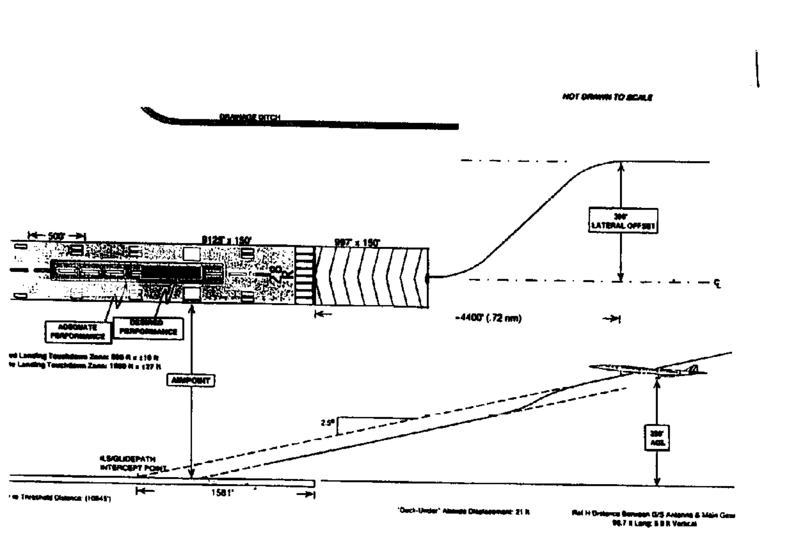
Tools for the Evaluation Pilots



Discrete Tracking Task

Figure 20-1 FAA APC Rating System





APC/PIO Workshop

NASA Dryden Flight Research Centre
Edwards, California
6-8 April 1999

Graham Weightman, JAA (UK CAA)

APC/PIO Workshop
Dryden Flight Research Centre, 6-8 April 1999

- Initial discussions with FAA in the JAA Flight Study Group (FSG) on proposed APC text for draft revision to FAA Flight Test Guide (AC 25-7X) beginning early in 1996
- JAA submitted comments on AC 25-7X (September 1996)
- Further discussions on APC in FSG (reference Flight Working Paper 599 prepared by FAA)
- JAA has reserved the APC text for the first issue of the JAA Flight Test Guide (based on AC 25-7A and to be published for comment shortly) pending further work

APC/PIO Workshop
Dryden Flight Research Centre, 6-8 April 1999

- FSG established an ad-hoc Sub-Group to work with FAA on harmonised guidance material for APC
- FAA (Mel Rogers) invited to chair Sub-Group
- First "kick-off" meeting in Braunschweig, Germany in January 1999. CAA, LBA, DGAC/CEV, FAA, Aérospatiale, Airbus and Boeing/AIA present
- Intention to work largely by E-mail
- Target: Draft revision of FWP 599 by June 1999


PIO Flight Test Experience at
Boeing (Puget Sound)
--and the need for more research
B. P. Lee
Airplane Handling Qualities
Boeing Commercial Airplane Group
Seattle, WA
April, 1999

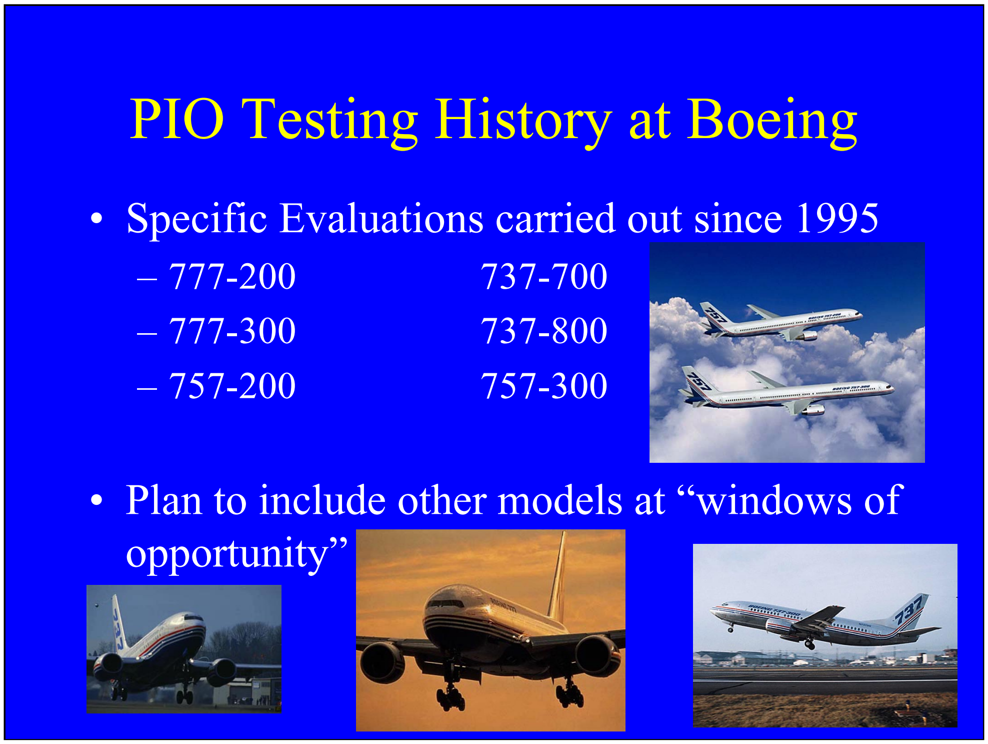
Introduction and Disclaimer

- This presentation represents a snapshot in time with regard to Boeing's flight test experience with Pilot-Induced Oscillations.
- The information contained herein is presented in the hope that in sharing technical information, safety can be enhanced through cooperative focus of research, and reduced duplication of efforts.

This presentation consists of two parts.

The first is intended to let the technical community know about Boeing (Commercial) flight test activity with respect to PIO. The scope of aircraft models tested, the kinds of data collected, and experience regarding various specific evaluation maneuvers will be discussed.

The second part of the presentation contains suggestions for focus areas in which the current state of analytical techniques is not adequate to address many very real situations which arise in the testing of large commercial jet transport aircraft.



Boeing Commercial Airplanes takes Pilot Induced Oscillations very seriously and endeavors to understand the phenomenon to insure that its products do not exhibit these adverse characteristics. Since 1995, Boeing has undertaken to evaluate a number of airplane models, and have a plan in place to evaluate others as opportunities present themselves.

As can be imagined, fully instrumented airplanes are not always easy to come by, so data is acquired whenever it is available.

Intent of Generic Test Program

- Evaluate Each Boeing Airplane Model
- Collect Data
  - End-to-End Open Loop Dynamic Response
  - Control System Response
  - Qualitative Evaluation During High Gain Tasks
  - Quantitative Evaluation During High Gain Tasks
- Document Lessons in Design Requirements

At the outset, Boeing conceived a generic test program which had the intent to conduct specific evaluations for PIO tendencies on each Boeing airplane model.

These evaluations were multi-faceted and intended to acquire four different types of data. These included:

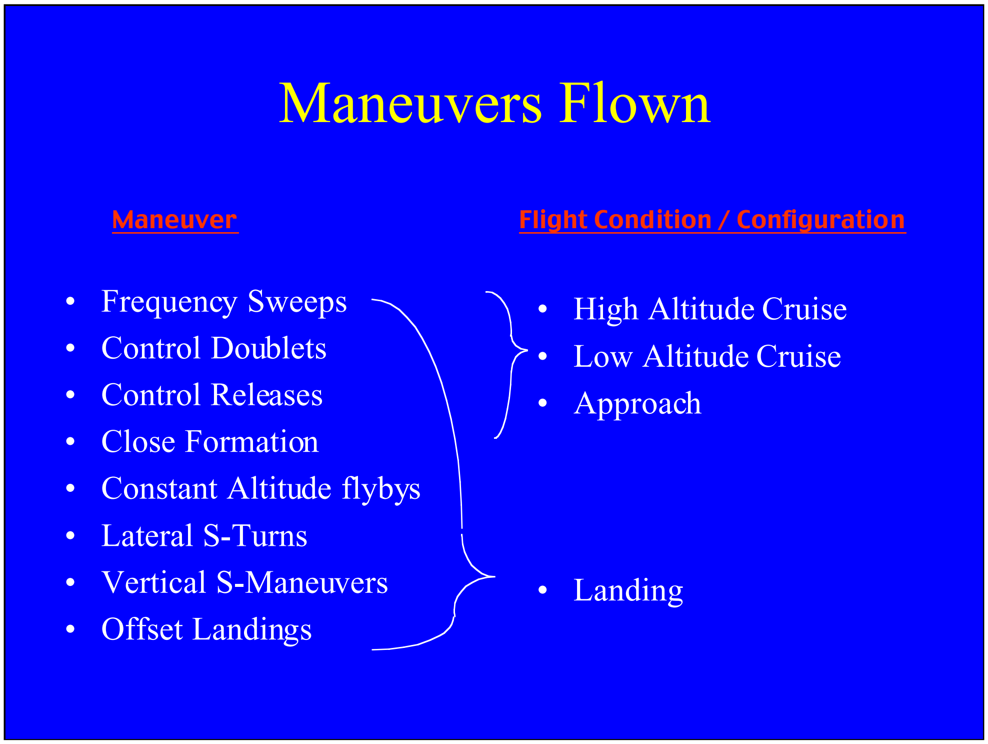
•end-to-end open loop dynamic response

•conrol system response data

•qualitative evaluation during high gain tasks

•quantitative evaluation during high gain tasks

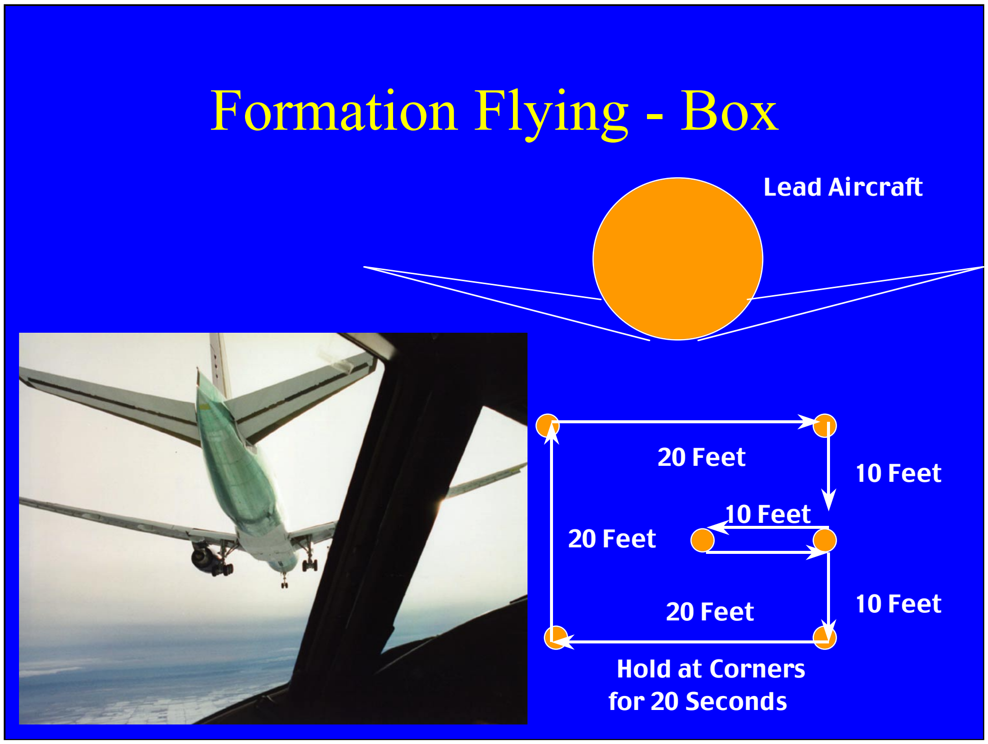
In addition to collecting the data, the results of the testing and subsequent analysis would be documented as lessons learned in internal design requirements.



The primary maneuvers in the generic plan are shown on the chart.

Open loop airplane and control system response data and the qualitative close tracking task (formation flying) is collected at high and low altitude cruise, approach, and landing conditions. The runway work is done only in the landing configuration.

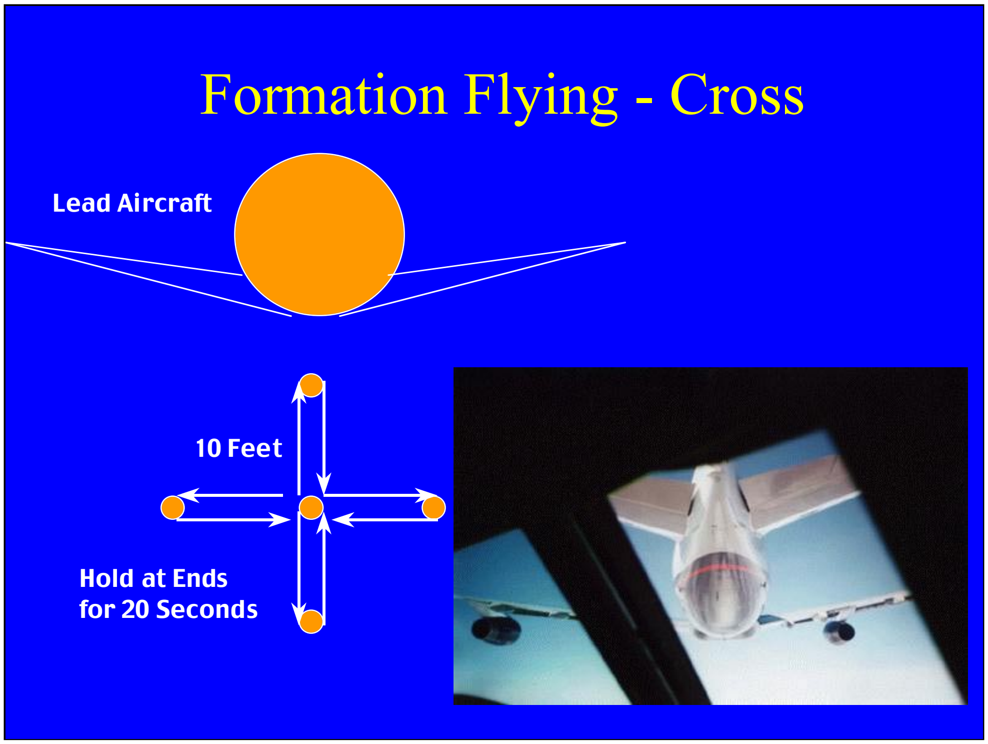
Open loop response data collection, consisting of frequency sweeps, control doublets, and control releases are self explanatory, and not described further.



A number of specific maneuvers have been used as close tracking tasks in up and away flight. One of the most effective has been close formation flying. A particular difficulty in implementation of this technique is that it is mostly qualitative in nature. Accurate measures of pilot-in-the-loop performance and and ways to adequately feed it back to the pilot have not been identified. Although discussions of over-the-shoulder cameras, heads-up displays, and differential GPS installations have taken place, none have as yet been implemented.

One maneuver used as a piloting task is the formation box maneuver, shown here. Once the pilot is established in a close refueling position (thought of as the center of the box), the pilot is asked to rapidly and aggressively acquire a new position 10 feet to the right. This new position is to be held as closely as possible for 20 seconds at which time the pilot is asked to acquire a new position 20 feet below the last. This is similarly held for 20 seconds. The maneuver proceeds around the "box". This maneuver combines a gross acquisition task with close tracking in a very high gain environment, and combines both longitudinal and lateral-directional axes.

The inset shows flying this maneuver with a 777-300 flying against another 777-300.



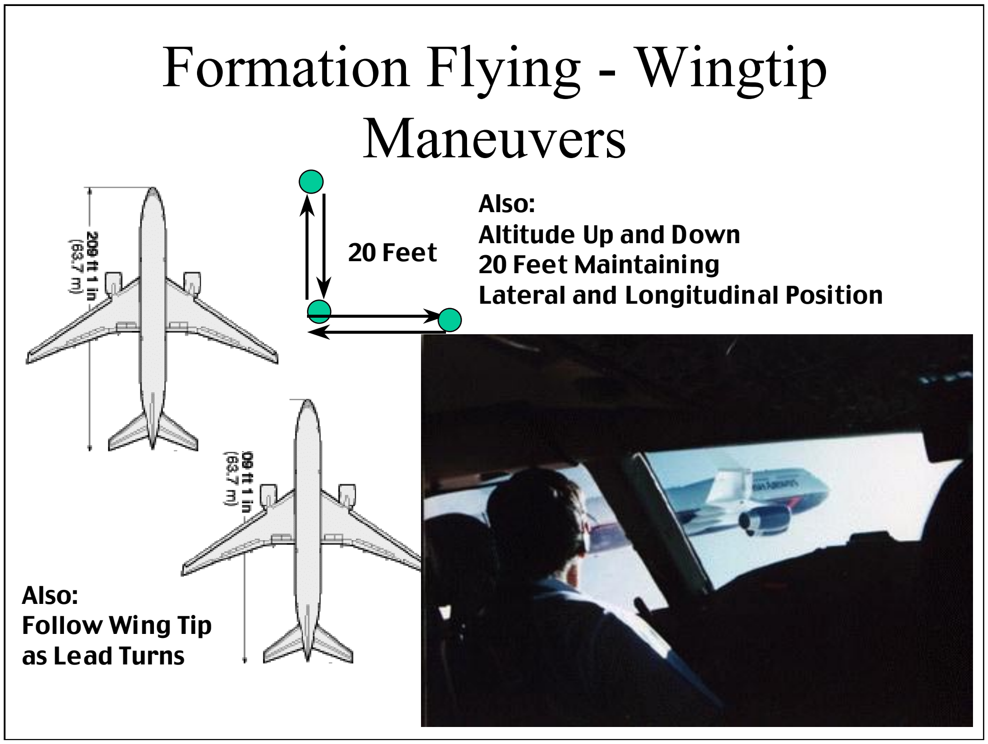
A second maneuver used is the formation cross maneuver. Execution of this maneuver is similar to that for the box.

One element which makes these maneuvers interesting in flight is that the trail airplane is flying in a curved flowfield. What this means is that to hold at the lateral ends of the cross requires flying in sideslip, which adds to pilot workload.

The inset shows this maneuver being flown in a 777-200 against a 747-400.

When transitioning to the approach and landing configurations, the lead aircraft also transitions in order to match flight speeds. Shown here, the trail pilot is looking rather directly at the upper surfaces of the very large triple slotted flaps of the leading 747.

Now while the vertical tail of the trail airplane is certainly immersed in the wake of the lead airplane in all conditions--and the buffet is noticable--the wake grows considerably for these flap down conditions. This increased the workload for the 777 airplanes, but the attendant buffeting was simply unacceptable for the shorter, lighter 737 airplanes. The task was not possible given the severity of the buffeting for that (737) airplane. So the entire task was moved to the wingtip of the lead airplane.



While the wingtip formation maneuvers were planned for all airplanes anyway, it was discovered that this was the only practical position to evaluate the flaps down conditions for the 737.

The wingtip maneuvers are shown here, including transitions fore and aft, in and out, and up and down. In addition the trail airplane was asked to follow the lead through turning maneuvers, keeping station on the wing tip.

These maneuvers proved to be very demanding. Compared to the refueling position, the wingtip position provided a much smaller target (the wing tip itself), which the pilot could see with better precision, and the target was much more active. Especially as the leader turned, the wingtip moved around significantly, generating a very demanding tracking task.

The inset shows a 777-200 flying against the 747-400 in the wingtip position. The evaluation pilot is focused very intently on what the lead aircraft is doing. The situation is just as dramatic when viewed from the lead aircraft.

This is a 737-700 being flown against a 737-800. The distances are short, and pilot gain is very high.

Formation Flying Summary

- Single Highest Gain Task
- Maneuvers Combine Acquisition with Tracking
- Learned Task Requiring Experience
- Wingtip Tracking Probably Most Effective
- Difficult to Measure Performance (and Feed Back to Pilots)
  - DGPS in the Future?
- Difficult to Enforce Performance Requirements
- Difficult to Get Consistent Level of Aggressiveness

To summarize Boeing experience with close formation flying as a maneuver to explore APC tendencies, it can be said that it provides a very high gain task which combines gross acquisition with tight tracking.

At the same time, it is very difficult to measure the pilot/vehicle performance and feed that back to the pilot in a meaningful, quantitative way. In addition, and perhaps because of the lack of performance information, it is very difficult to achieve consistency in aggressiveness across several evaluation pilots.

Constant Altitude Flyby

- Intended to "Extend" the Flare for Analysis
- Involves both Acquisition and Tracking
  - Fly ILS to 50 Feet
  - Flare and Maintain 50 +/- 10 Feet for Length of Runway
  - Maintain Centerline
  - PNF Calls Radar Altitude

Another set of maneuvers used to explore APC tendencies has involved flying close to the runway. Originally, the flyby task was conceived to provide insight into the pilot/vehicle combination in the flare. Upon examination, if done properly, a flare maneuver takes only a few seconds. On large transports with natural frequencies on the same order, it is difficult to gain much understanding about the interaction. So this maneuver was conceived to provide an extended time period for data gathering. The maneuver involves acquisition and tracking in a high precision environment.

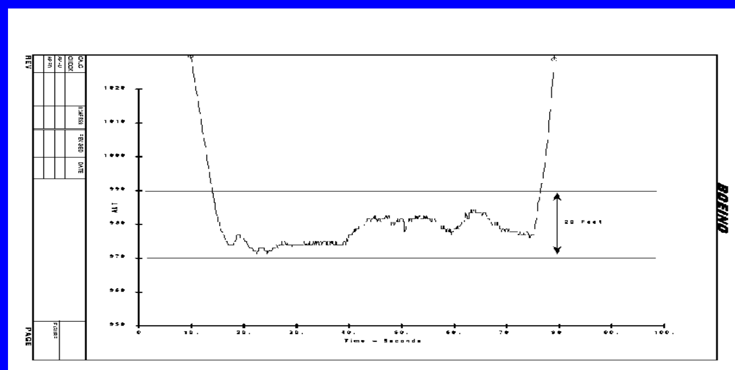
The pilot is asked to flare and maintain 50 +/- 10 feet for the length of the runway. Typically, the pilot will close a loop around radar altitude, with the pilot not flying calling radar altitude continuously. During the maneuver, the pilot is asked to maintain the runway centerline.

It was discovered that the most difficult part of the task was making the power adjustment in the round-out. Too little power and airspeed would bleed away in the level segment; too much, and the airplane would accelerate or climb.

Pilots descried the task as challenging but not impossible.

Flight Performance

- Pilots Characterized Task as “Demanding, but not Impossible”
- Power Setting in Flare Requires Precision



An example time history shows that the desired performance level could be met. It is interesting to note that at the particular runway used for this test, there is a “hump” in the runway at about the midpoint. That is to say that the runway elevation is higher in the middle than on either end. With the pilot closing on radar altitude, the maneuver proceeds nicely until that point, at which time a power adjustment is required as the runway “falls away” from the airplane. This “feature” in the local topography provided a convenient increase in workload for the pilot flying the task.

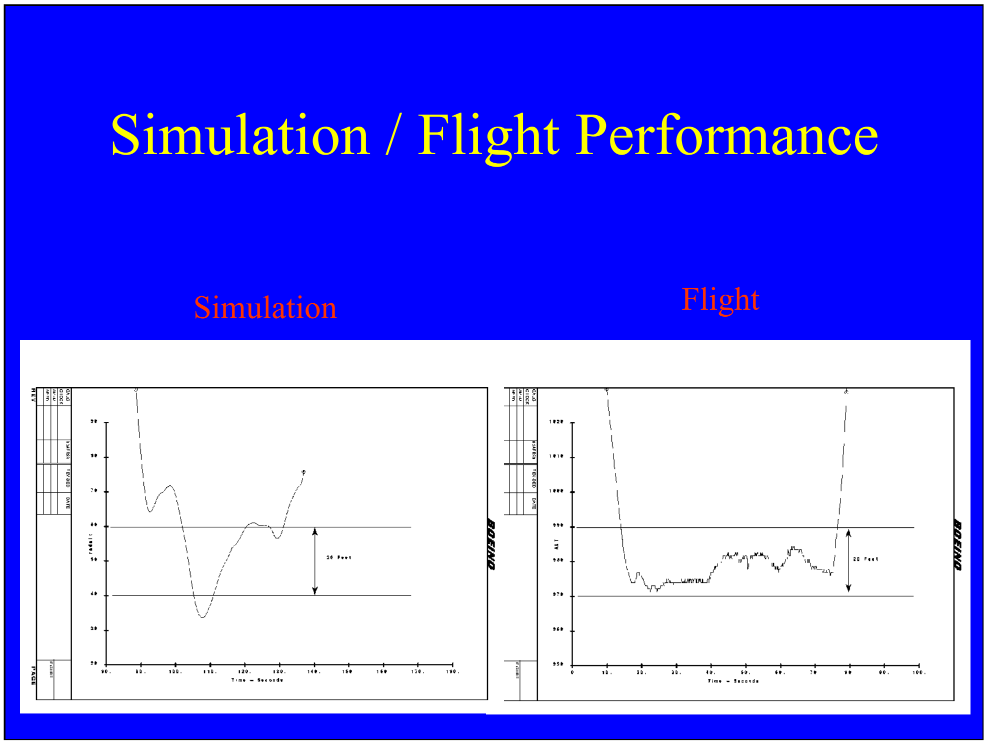
Comments on Use of Simulation

- Most Valuable for Pilot Familiarization and Practice of Maneuvers
- Easy to Measure Pilot Performance
- Lack of Cues Makes PrecisionTasks More Demanding
  - Depth Perception
  - Visual Acuity/Scene Content
  - Motion
- Lack of Urgency Allows Higher Pilot Gain
- PIO Results are Largely Inconclusive

At this point, a small diversion into the subject of the use of simulation is in order. Boeing uses engineering simulation, with pilots in the loop, both fixed and moving base for this kind of testing. As a result of this experience, these sessions are seen as more valuable for pilot familiarization with the task than for collecting data regarding APC tendencies of a particular configuration.

While it is easy to measure and feed back pilot/vehicle performance in the simulation, there are a number of deficiencies as well. On-ground simulation is simply not the same as flight. A number of pilot cues, which may or may not be important for a given APC evaluation are lacking or of insufficient quality. In addition, the pilot knows it is a simulation, and so there is a general lack of urgency. Pilots have been seen to make control movements in simulation which they simply would not do in flight with a large transport.

Based on this experience, PIO results from simulation alone are considered largely inconclusive.

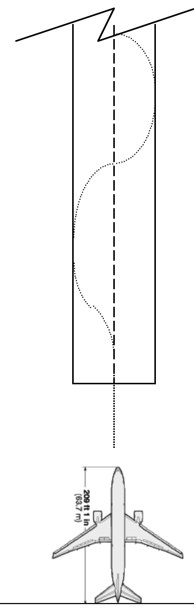


One example is shown in this comparison. On the right is the in-flight result from the straight fly-by maneuver shown previously. On the left is a time history taken in a fixed base simulator. For whatever reason, the pilot is simply not able to fly the required task in the simulator.

Use of simulation can certainly flag the potential for untoward tendencies, but the effects of myriad cueing issues are yet unanswered. As a result, ground-based simulation is not yet seen as a viable substitute for flight testing. However, it is quite valuable in getting pilots familiar with the maneuvers involved and useful as a tool to explore maneuver set up, etc.

Lateral S-Turns

- Intended to Increase Workload by Adding Axis
  - Fly ILS to 50 Feet
  - Acquire as Rapidly as Possible one Runway Edge Line
  - Acquire as Rapidly as Possible the Opposite Edge Line
  - Repeat for Length of Runway
  - Maintain 50 +/- 10 Feet
  - PNF Calls Radar Altitude

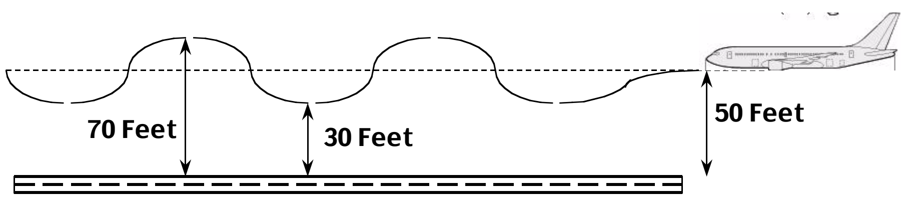


In an attempt to increase the workload encountered on the fly-by maneuver, an additional task was superimposed. The lateral S-Turn maneuver asks the pilot to proceed as in the flyby, except once established at 50 feet, the pilot should, as rapidly as possible acquire alternate runway edge lines and continue for the length of the runway.

This is a very impressive maneuver for an airplane with a 200 foot wingspan at 50 feet above the runway.

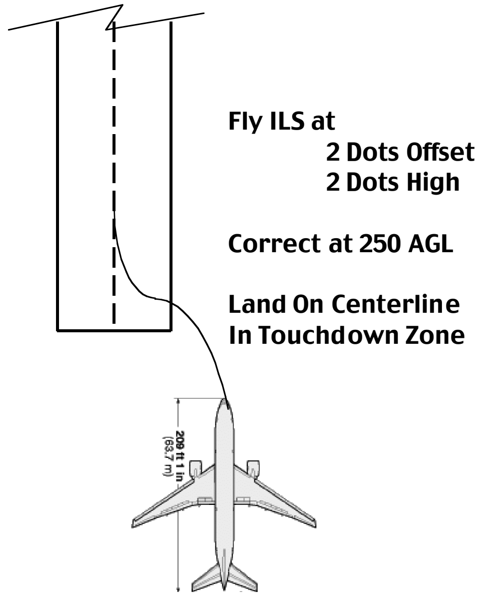
Vertical S-Maneuvers

- Further Increases Urgency
  - Fly ILS to 50 Feet and Capture 50 +/- 10 Feet
  - Acquire as Rapidly as Possible 30 +/- 10 Feet
  - Acquire as Rapidly as Possible 70 +/- 10 Feet
  - Repeat for Length of Runway
  - Maintain Centerline
  - PNF Calls Radar Altitude

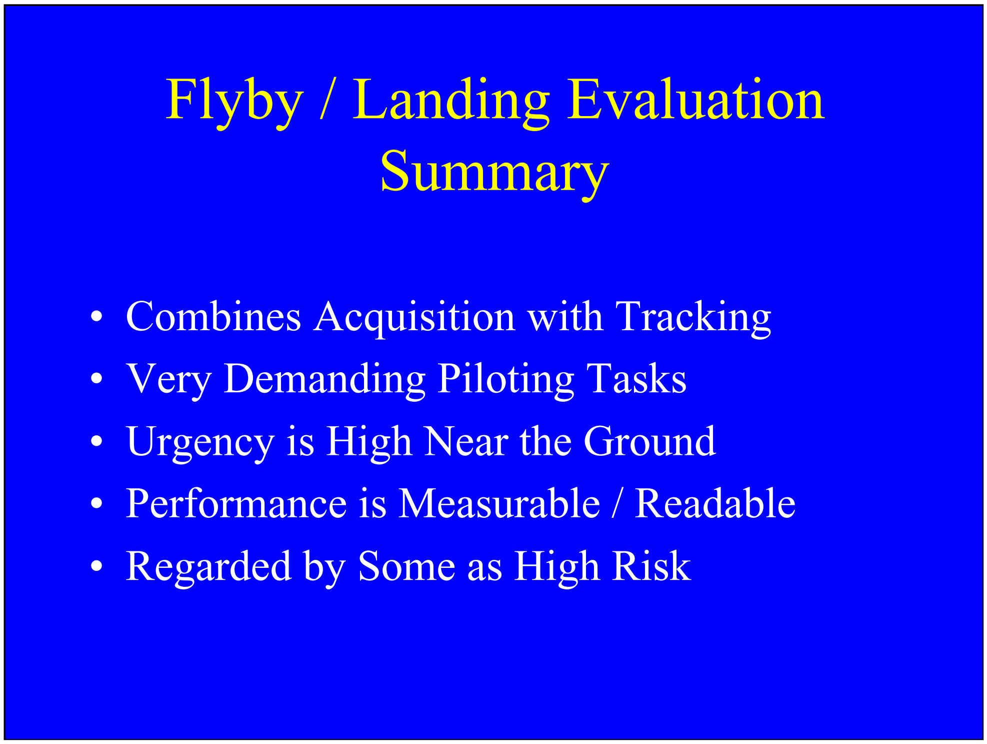


An additional increase in urgency was achieved when the pilots were asked to perform a vertical S-maneuver. Again leveling at 50 feet, the pilot is asked to rapidly and aggressively acquire 30 feet and 70 feet alternately. While this is a single axis task, urgency is very high in a large airplane maneuvering vertically close to the ground.

Offset Precision Landing



The offset precision landing is a maneuver used by most testing organizations to investigate PIO tendencies, and Boeing has used it as well. The familiar set-up for this maneuver is to align on the drainage ditch beside the runway at Buffalo, NY, as used by Veridian/Calspan. Most airports do not have this convenient landmark, however, so Boeing has adopted a multi-axis task which involves flying the ILS intentionally offset. The offset chosen is 2 dots laterally and 2 dots high. At 250 AGL, the pilot is asked to correct to the centerline and land in the touchdown zone. This is a very challenging maneuver at low altitude.



For the low altitude tasks, Boeing has chosen maneuvers which combine acquisition with tight tracking in very demanding tasks. Being close to the ground increases the pilot's urgency and thus pilot gain. Because the target (the runway) is fixed in space, it is relatively easy to measure quantitative pilot/vehicle performance.

A consideration worthy of note is the proximity to the ground with a very large airplane is regarded (properly) by some as high risk. The risk of encountering undesirable characteristics in such a situation must always be weighed in the test planning process.

Other Maneuvers in the Toolbox

- Flight Director Tracking
  - Sum-of-Sines
  - Steps-and-Ramps
  - Log Frequency Sweeps
  - Added Discrete Disturbances
- Bank Angle Captures
- Heading Angle Captures
- Lateral Pilot Handoff
- Full Rudder Sideslip in Ground Effect
- Constant Track Rudder Step

While the "generic" maneuver set is defined as above, a number of other maneuvers have been used for specialized applications.

Flight Director tracking has been used in some cases, with a number of different input functions. In all cases, the pilot is shown only the error between commanded attitude and actual attitude, forcing a compensatory tracking scheme. Log frequency sweeps provided both insight and broad frequency coverage for future analysis. The ability to insert discrete disturbances into the flight director signal also provided additional insight.

Bank angle and heading angle captures are standard evaluation maneuvers. The lateral pilot handoff involves one pilot initiating a rolling maneuver, relinquishing command of the airplane to the other pilot while at the same time calling out a bank angle to capture. This is essentially a bank angle capture initiated from a non-zero roll rate.

Full rudder sideslips in ground effect are an attempt to investigate a landing de-crab maneuver in much the same way that the fly-by allowed investigation of the landing flare.

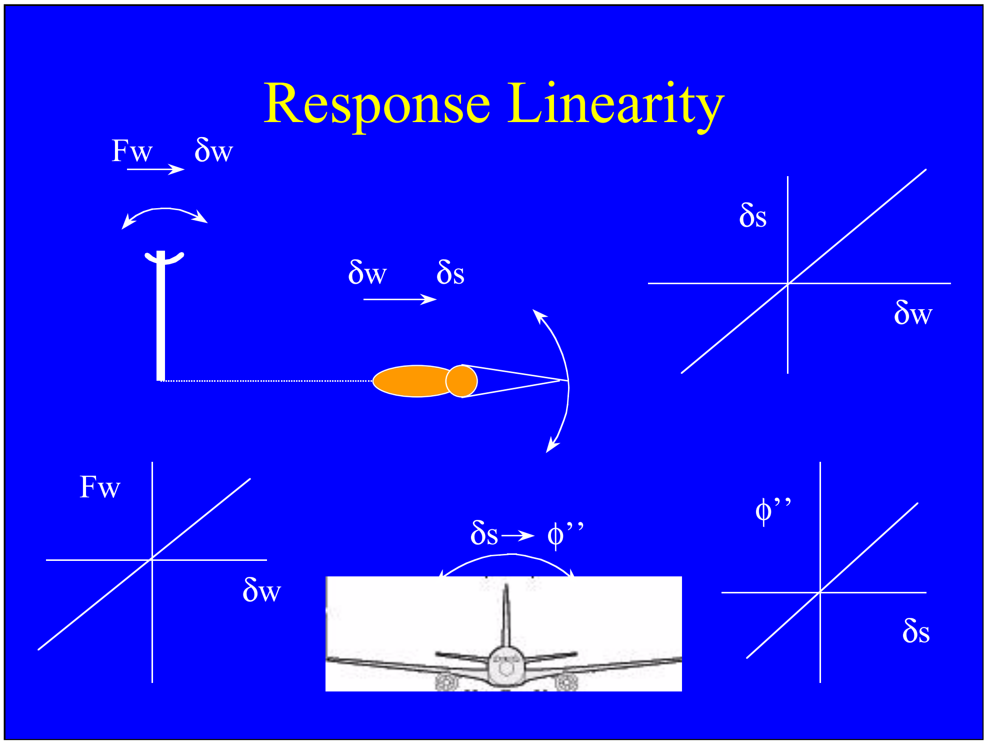
The constant track rudder step is an up-and-away maneuver in which the pilot inserts a rudder step and flys track (on the nav display) with wheel. This maneuver turned out to be very difficult to fly. While it is essentially a transition from crab to slip as in a crosswind landing, it proved unnatural to perform up and away on instruments.

Flight Test Evaluation Summary

- Boeing has Extensive Experience Flight Testing for PIO
  - Several Hundred Hours of Testing
  - Six Different Models
  - Large Number of Manuevers / Techniques
- No Single Maneuver / Technique has Proven to be Effective for Exposing PIO Tendencies
- Most Effective Testing Strategy Appears to be Careful Diligence During Normal Test Flying
- Prudent Handling Qualities Design Appears to be Effective for Prevention
- Evaluation Process Continues to Evolve

Through several hundred hours of flight testing to evaluate PIO tendencies over a large number of airplane models and involving a large number of specific maneuvers, no single maneuver or technique has proven to be effective for exposing potential PIO tendencies. The conclusion from this is that the most effective design strategy appears to be prudent attention to fundamental handling qualities design while the most effective testing strategy appears to be careful diligence during normal test flying. The testing which is done for development and certification of a transport airplane provides significant opportunities to be at remote corners of the flight envelope and investigate airplane characteristics.

Even so, the evaluation process continues to evolve and more new information is learned with each additional test program.



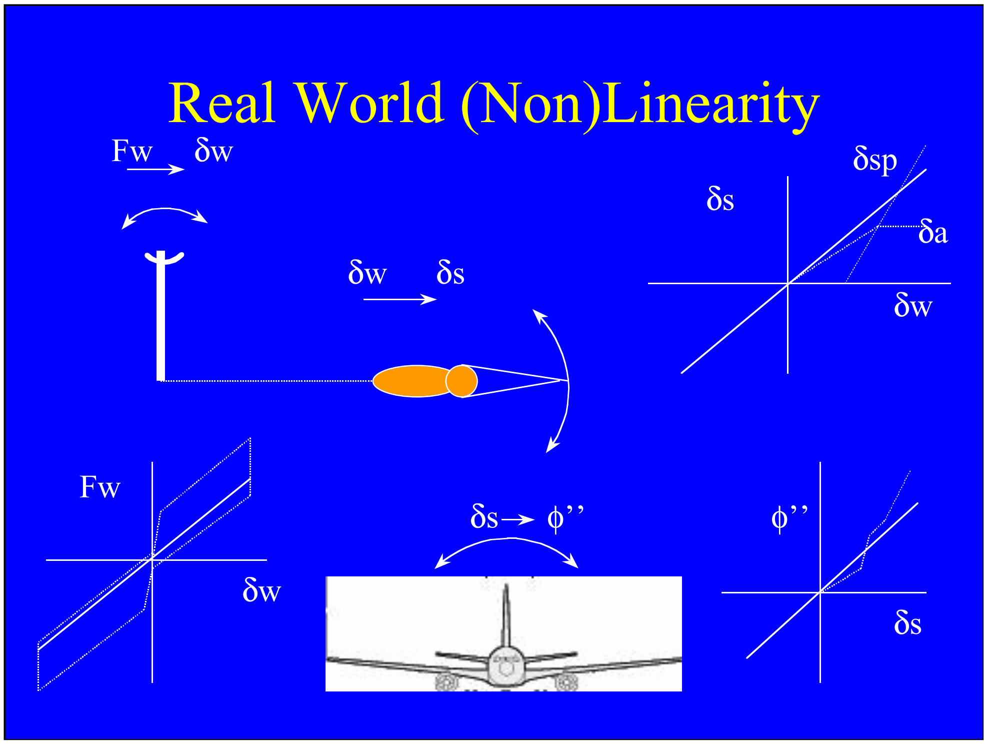
Moving from generic testing to identifying challenges for future work, this chart depicts a number of steps between the pilot's application of force to an inceptor and the airplane response.

In the upper left is a (crude) depiction of a column/yoke. As the pilot applies a force (Fw) to the wheel, the wheel would be expected to move. Moreover, as the sketch below it shows, it is normally assumed that there is some linear relationship between applied force and wheel deflection (δw).

For mechanical or displacement command systems, that displacement of the wheel should result in a corresponding displacement of an aerodynamic surface (δs), as depicted in the center sketch. Again, it is typically assumed that there is a linear relationship between controller displacement and surface displacement, as in the sketch in the upper right corner.

Finally, a surface displacement (δs) is expected to result in an acceleration of the airplane, in this case, a roll acceleration (φ''). In most cases there is a goal to achieve a linear relationship between these two as well, as shown in the lower right sketch.

These assumptions of linearity form the basis for the use of frequency domain analysis to study airplane dynamics and PIO.



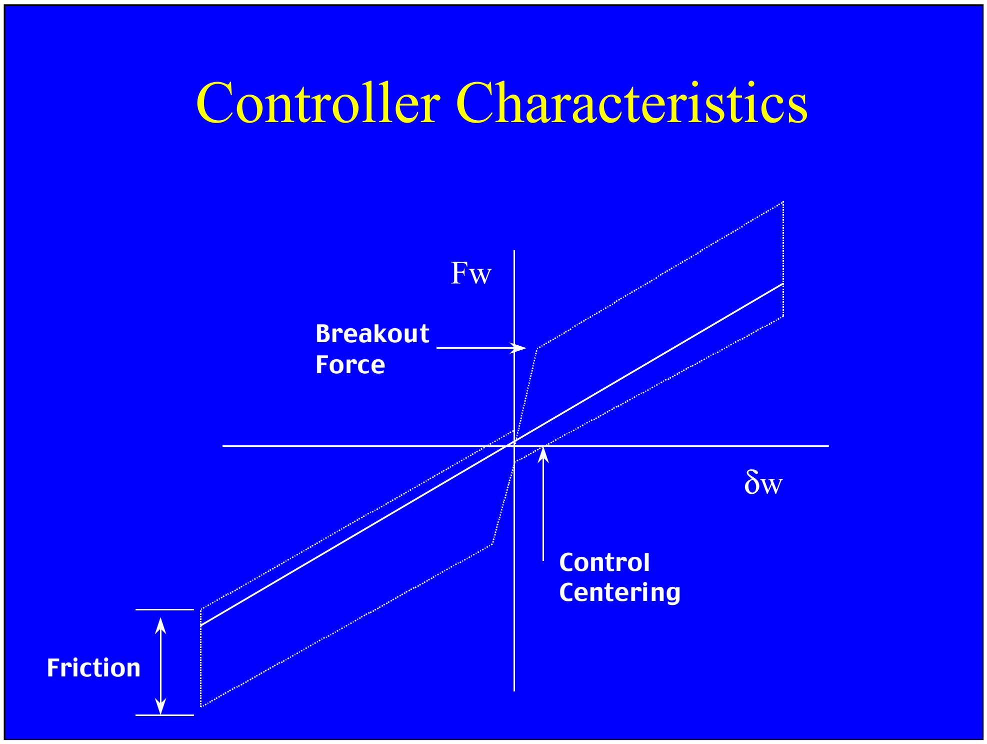
Unfortunately, the real world does not always conform to these assumptions.

In the presence of system friction, the control force to controller displacement relationship exhibits discontinuities and hysteresis. (lower left).

Modern transport airplanes typically use a combination of aileron and spoiler surfaces for roll control, each of which may be scheduled on different deflection curves, have different rate capabilities, etc. (upper right)

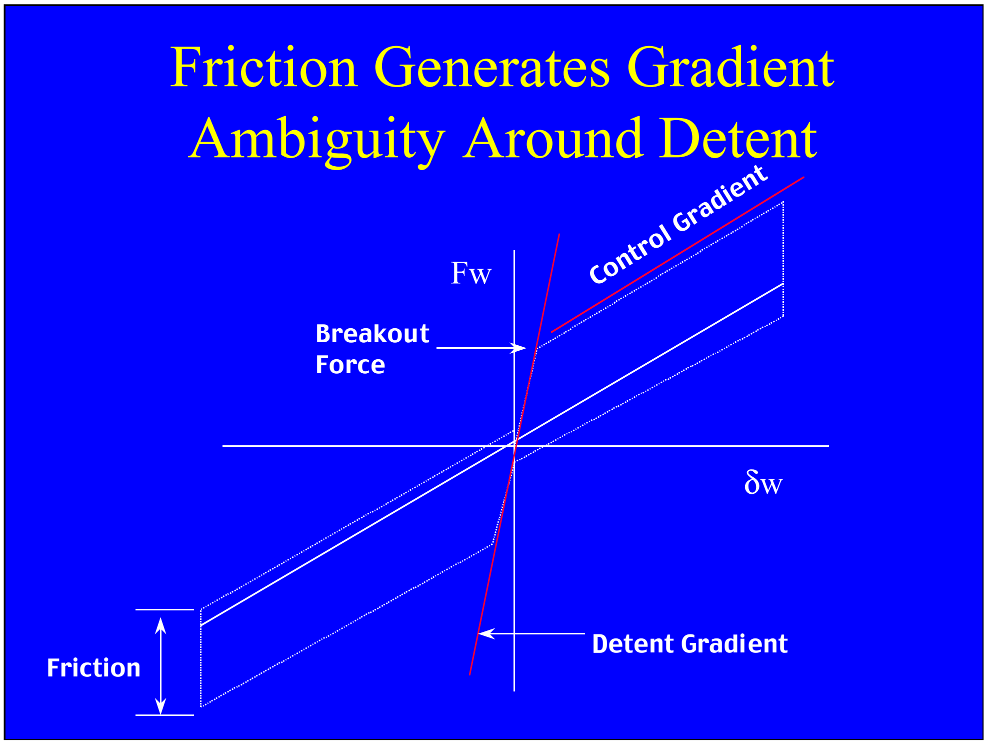
Finally, though a linear roll rate capability is desired, it is rarely achieved in practice.

Each of these sources of nonlinearity causes difficulty in application of the typical analysis methods for PIO which are found in the literature. To focus on the need for methods to accommodate these characteristics, each is discussed in detail in what follows.

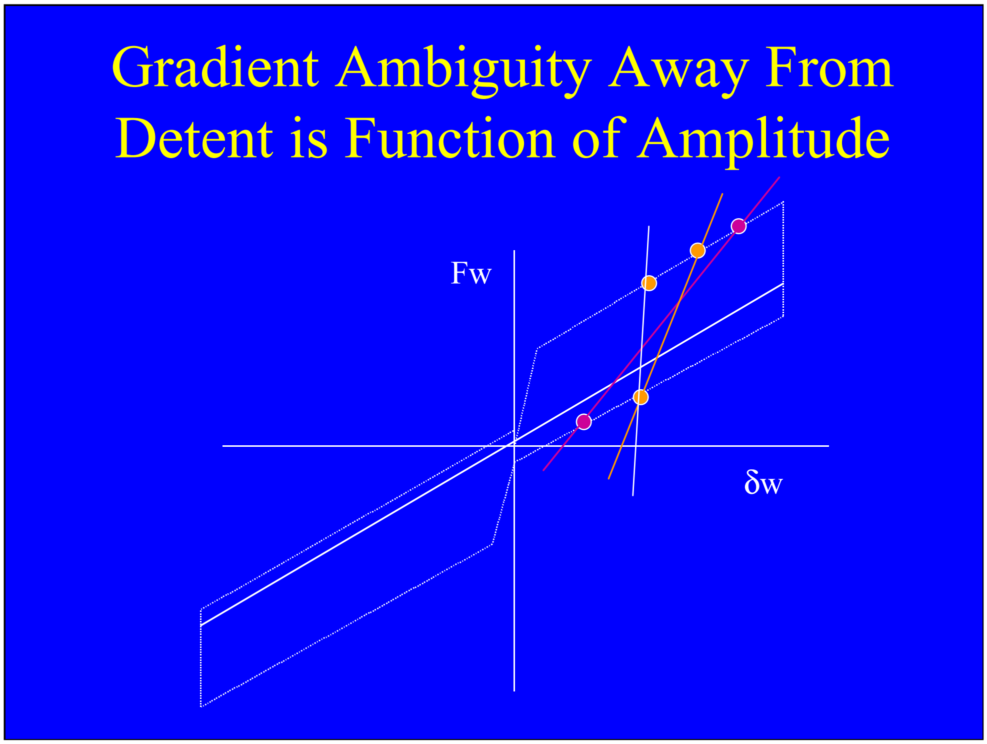


Starting at the pilot's fingertips, while most agree that linear force/displacement characteristics are desirable, all control systems have friction. In particular, large transport aircraft with mechanical control systems can have friction levels which are not trivial.

One thing that friction brings is hysteresis. In order to achieve some degree of control centering,, a breakout force is typically added. This breakout essentially offsets the force/displacement curves around zero, allowing the wheel to return to the center position when no force is applied.



The presence of this breakout produces a force/displacement discontinuity. The presence of a slope change can have detrimental effects on pilot predictability. The pilot loses his sense of how much force to apply to get a desired displacement. Moreover, the slope discontinuity is right in the center of the control operating range, where the pilot works the most. This can make small displacements, e.g. those required for tight tracking around neutral wheel, difficult for the pilot.

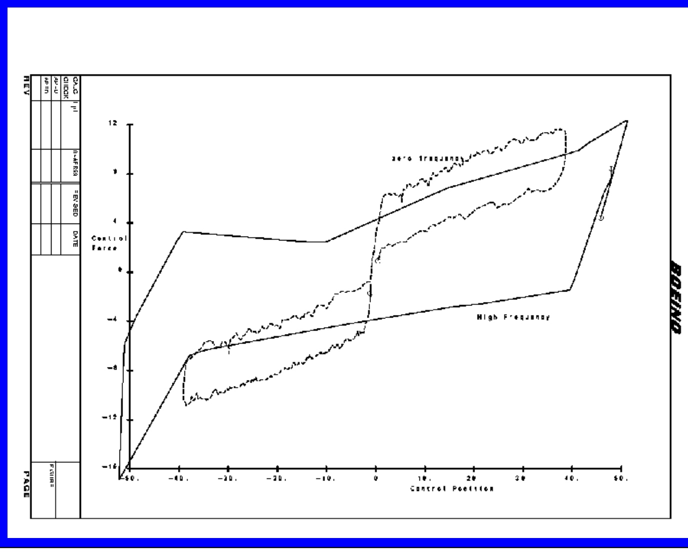


Away from the detent, the presence of friction and the associated hysteresis causes a similar gradient ambiguity. Moreover, the degree of ambiguity is a function of the size of the input for a given friction level.

This is significant for example in a decrab maneuver for a crosswind landing. The gradient of the force required to move the wheel a given amount in each direction around a (non-zero) trim point depends on how big the input needs to be.

Again, predictability from the pilot's point of view is compromised.

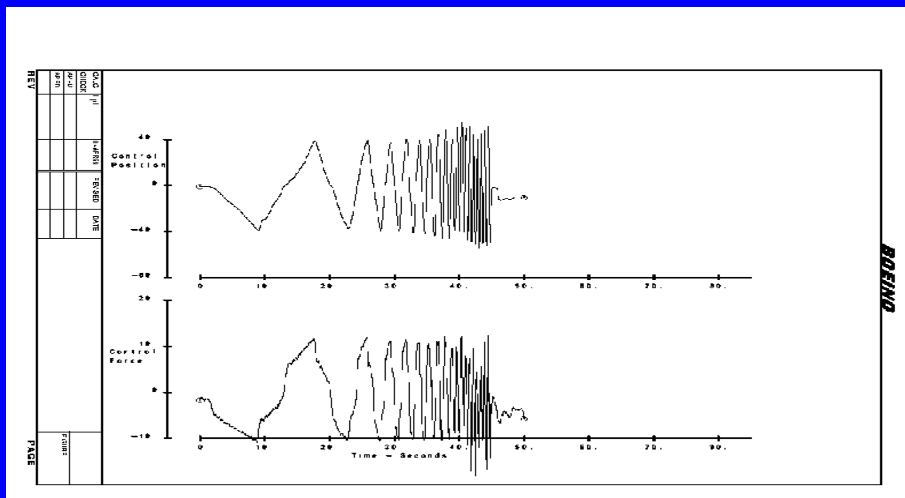
Dynamic Inertial Effects on Controller Characteristics



The static force/displacement characteristics of the controller are only part of the story. Since the control system itself has mass (and large transports can exhibit significant mass characteristics), the force/displacement characteristics vary as a function of the frequency or speed at which the control is moved.

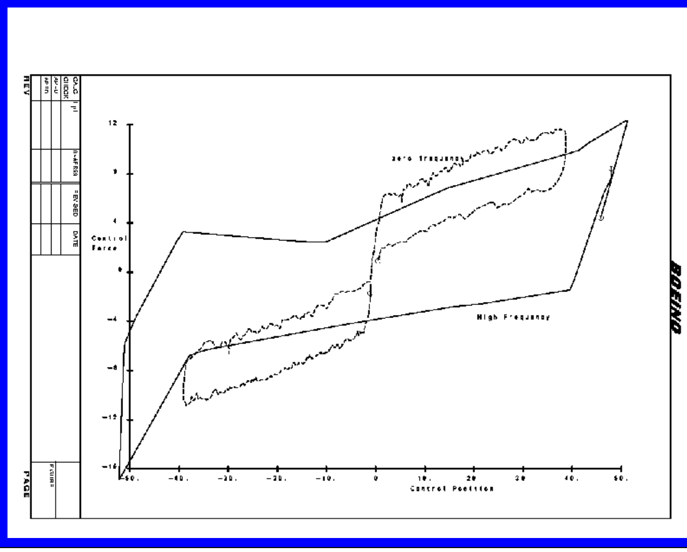
What is shown is force vs displacement at near zero frequency and another sweep at significantly higher frequency. It is clear that the two curves are significantly different. The center detent is not even evident in the high frequency case, the slope of the return (long lower path going from right to left) at high frequency is not similar to the near zero frequency case, and there are some non-linear characteristics near the ends of the travel.

Dynamic Inertial Effects Depend Also on Path (History)

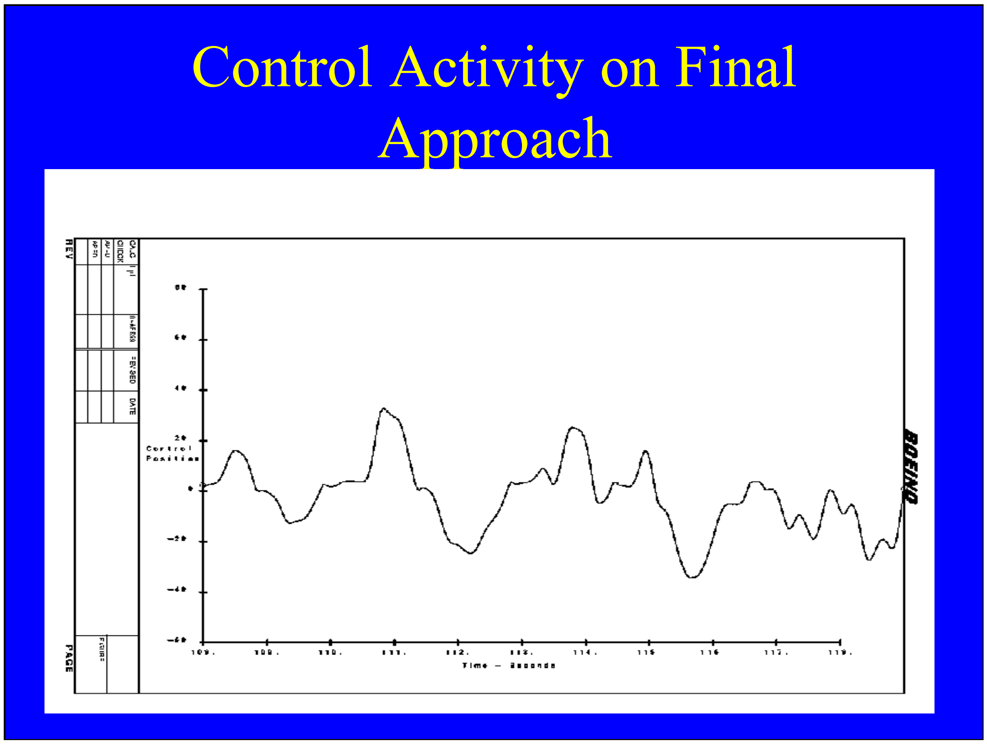


Now, the high frequency sweep on the previous chart was taken from the middle of a log frequency sweep. Had a single high frequency sweep been undertaken from a standing start, the force/displacement curve would have looked different yet. All of this is because the control system itself has mass and inertia.

Dynamic Inertial Effects on Controller Characteristics



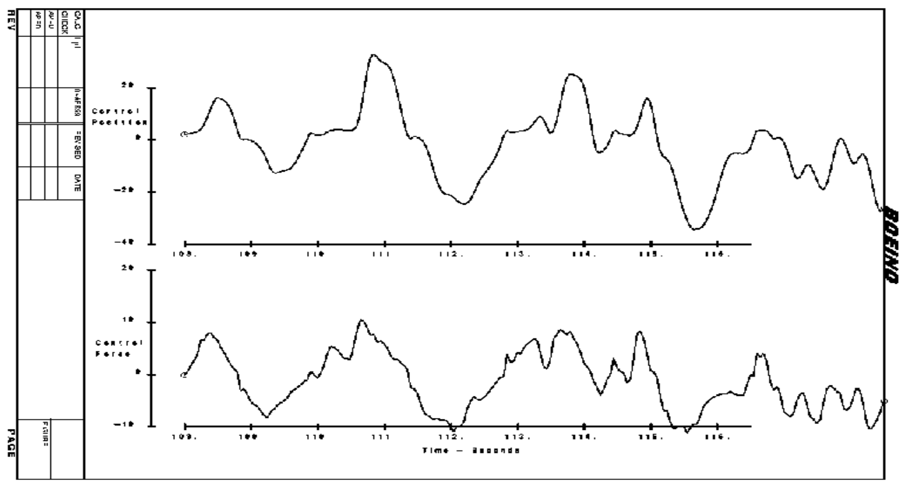
The end result is again a question of predictability. At any given time in the flying of an airplane, the pilot needs to have some idea of how much force to apply to the controller to get to move to where he wants it to go. These dynamic characteristics cloud the issue and contribute to ambiguity.



What this has to do with real flying of airplanes is shown here. This is a time history of wheel position for a normal approach to landing. Wind was light, turbulence was not a factor.

What is unique about this is the pulse-like character of the wheel inputs. At the left hand side note the quick pulse as the wheel moves more than 15 degrees, then is taken back to zero in about a half second. This is followed by an equal pulse in the other direction. After a period of quiescence, the sequence is repeated at roughly twice the amplitude, still with very short duration.

Pilot / Controller Interaction

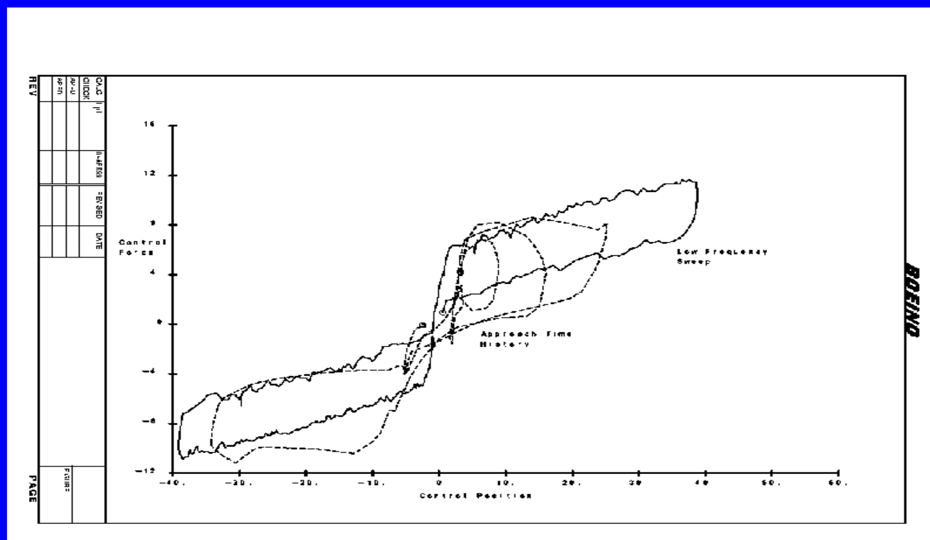


Just why this is happening can be further understood by examining the corresponding pilot force inputs.

Note that between the first and second position doublets, where the wheel is approximately zero, the force is not. In fact the pilot tried to move the wheel. There is a brief 5 pound input in which the wheel did not move. This is followed by a larger, nearly 10 pound input which generated the larger wheel deflection (upward on this plot) which the pilot immediately removed, and corrected in the other direction.

In this case, the wheel feels “sticky” to the pilot and small, smooth inputs are difficult. This degrades precision of control.

Effective Controller Characteristics



A phase-plane representation of the same sequence is overlaid on the near-zero frequency force/displacement plot for the same configuration. This illustrates the lack of predictability which is generated by inertial characteristics of the control system itself.

The result is that at any point in this dynamic maneuver, the pilot is unable to predict how much force to apply to generate what wheel position.

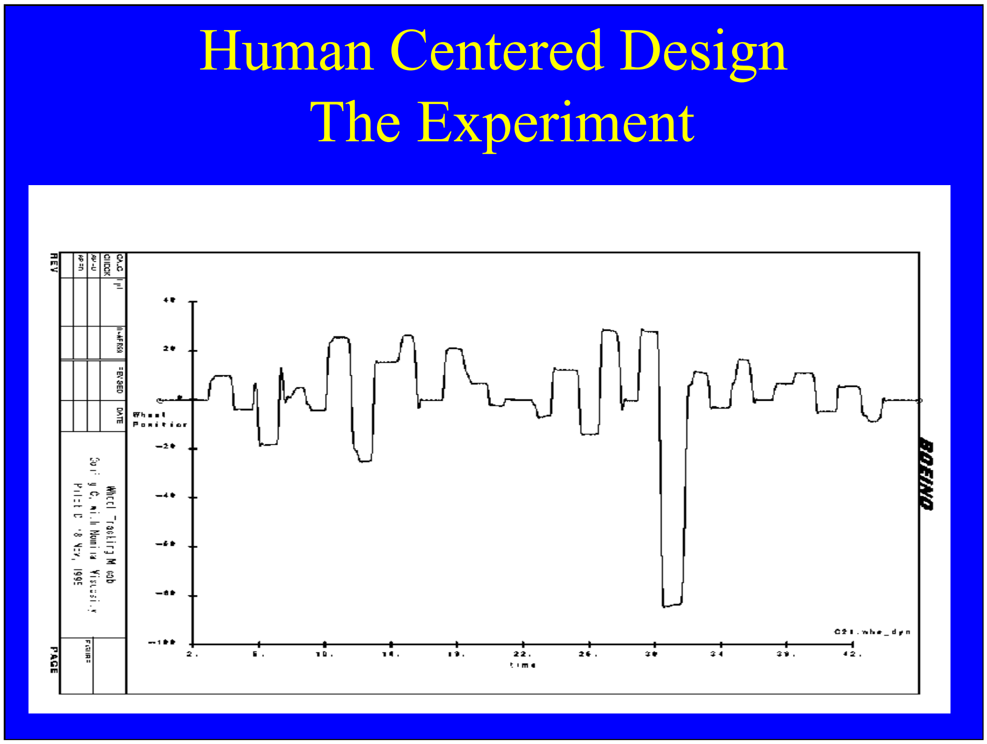
These kinds of controller effects are not adequately dealt with in the literature, and represent an area which is ripe for investigation.

These were dealt with at Boeing in the following way.

It is understood that the control system has a minimum inertia, damping, and friction. Any modifications cannot change those, although additions to each would be possible.

In addition, there are constraints on maximum force at the wheel stop (regulatory) and on the power to drive the system (e.g. if friction or damping get too high, pilots will be easily fatigued by simply moving the wheel around).

The challenge was to find desirable combinations of these parameters to improve the pilots ability to make smooth, predictable control inputs.

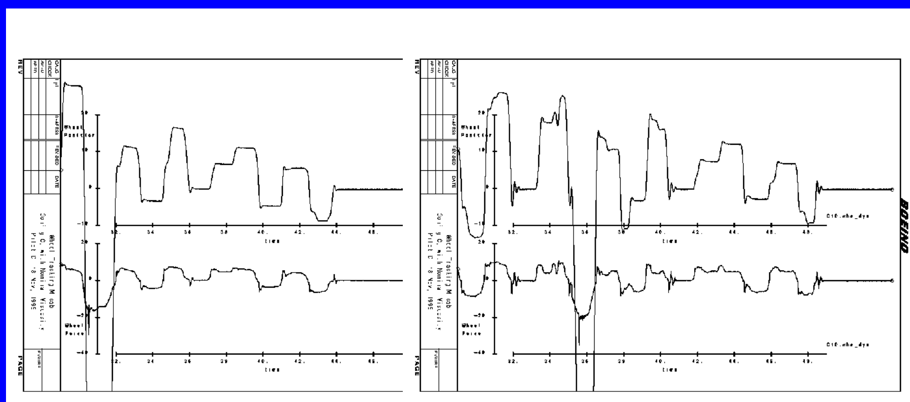


An experiment was designed for a high fidelity simulation in which the control loader characteristics could be changed to reflect the changes in the parameters. This is a time history of the wheel deflections commanded in the study. The pilots were asked to position the wheel according to this scheme.

This did not involve "flying" an airplane model at this point. It was simply a one-dimensional task to see if some combinations of friction, damping, and inertia were better than others for the pilots' ability to precisely position the wheel.

In looking at some results, the time period just after the full left wheel input will be examined.

Human Centered Design
Some Results



Some sample results are given here. In the time history plots, wheel position is on the top, wheel force is on the bottom.

For the configuration on the left, it is clear that the pilot was able to achieve the desired wheel positions accurately and quickly with little overshoot. Good damping is seen on the lower force trace, wherein the pilot used a small but well damped oscillatory force input in order to get a good square shaped response.

For the configuration on the right, it is just as clear that the pilot is having difficulty achieving the desired wheel positions. The force oscillatory at the corner points is not as well damped as before, and larger in magnitude.

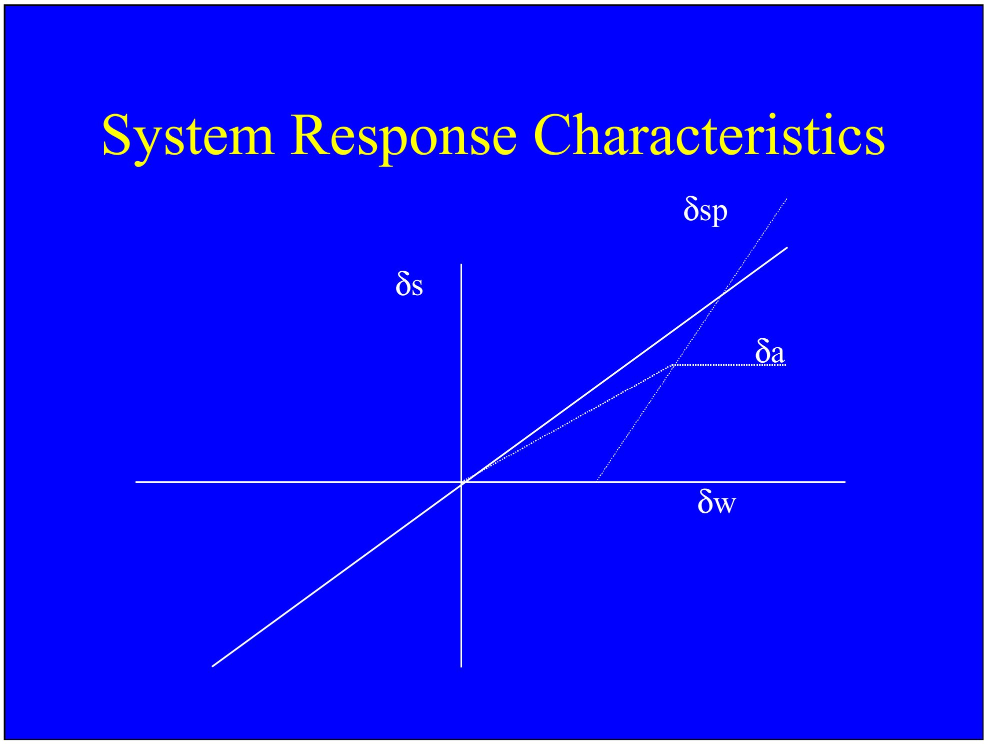
Application of Results

- "Best" Configurations (and one "Bad" one) Flown in Simulation for Pilot Opinion
- Best of Those Configurations Flown in Flight Test
- ...Results Indicate Improved Pilot Opinion, Improved Precision (Pilot Performance), and Less Structural Excitation

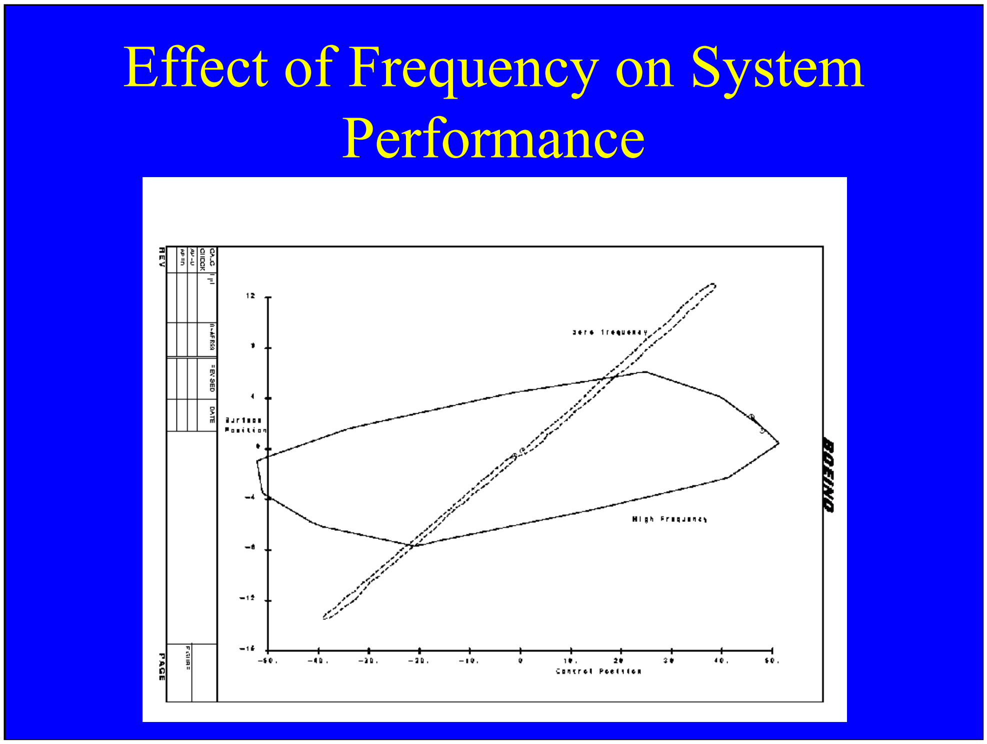
With the results from the single axis wheel positioning task, the "best" configurations were flown along with an airplane model, still in simulation, asking the pilot to perform operational tasks. This was also done with one configuration deemed "bad" by the single axis task, just to insure that the first results were not misleading.

The best combinations of friction, damping, and inertia from simulation were flown in flight test (airplane systems were modified to match the characteristics determined in simulation).

The results of the flight testing indicated that pilots did indeed both prefer the new feel configuration and found that it afforded them a higher level of precision in their maneuver performance. An unexpected benefit was the realization that with the new configuration maneuvers could be flown with less structural excitation.



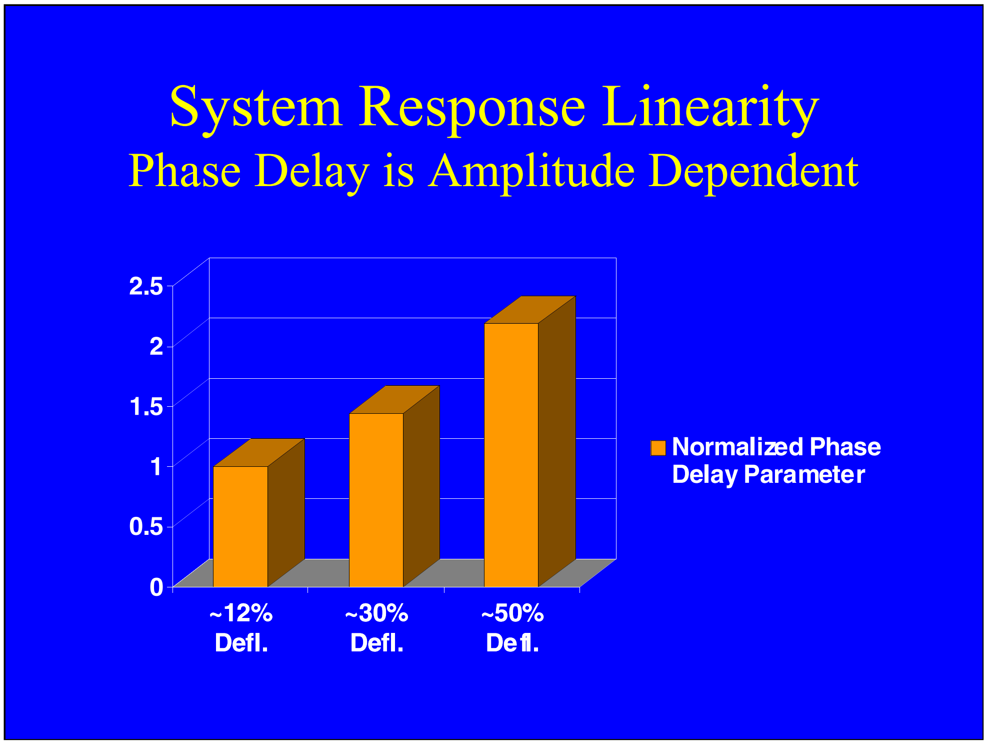
As was mentioned earlier, on modern jet transport aircraft, the roll control surfaces are often scheduled separately as a function of controller deflection. Ailerons and spoilers are often actuated on different schedules and with different rate capability actuators.



The presence of rate limits in any element of the system generates ambiguity with respect to surface position which is a function of the frequency of the controller motion.

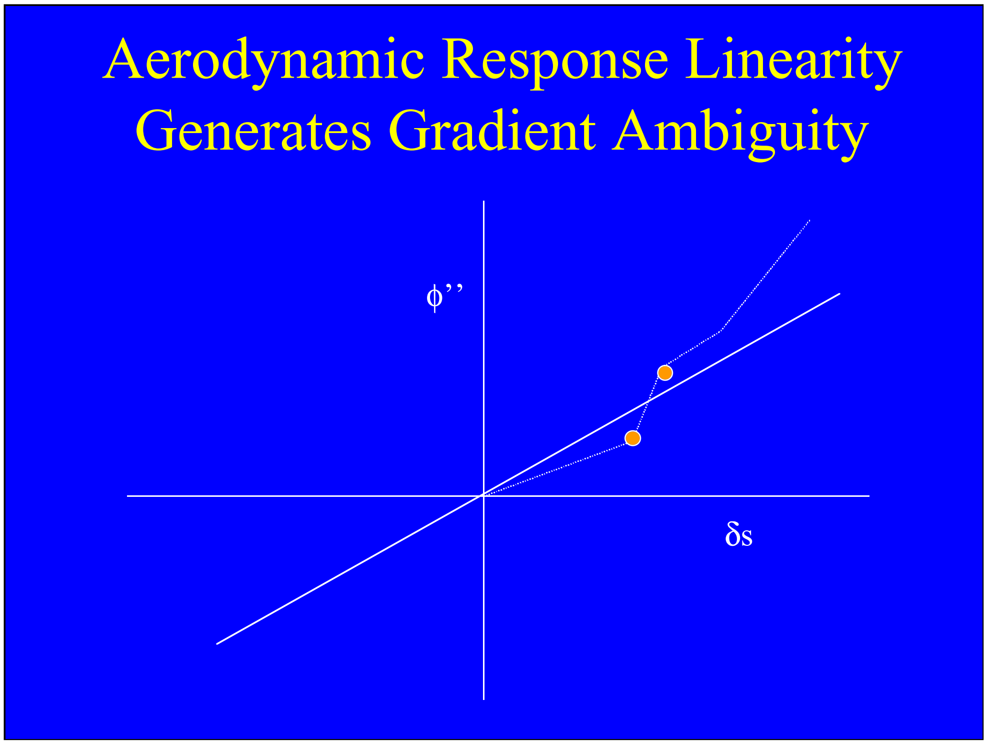
Shown here is controller position vs surface position. For the near-zero frequency case, the relationship is indeed close to linear. However, at larger frequencies, particularly past that required to saturate actuator rate limits, the relationship becomes more ambiguous.

To the pilot, this means that at any point in time, the surface position may not correspond to the controller position.



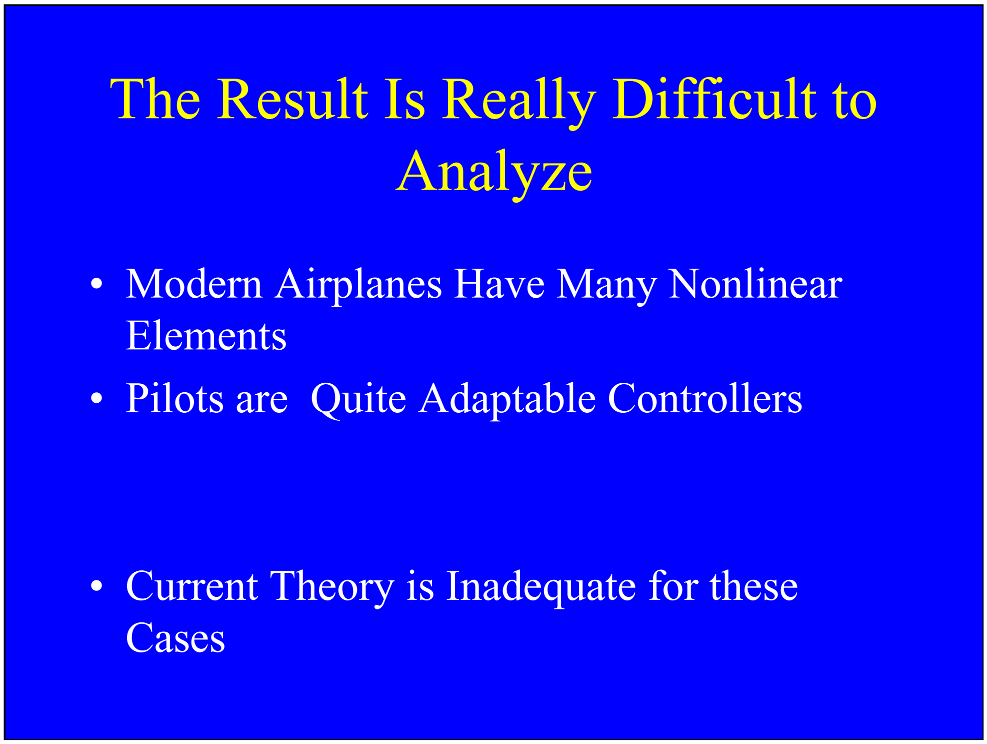
For cyclic motion of the controller, the rate limits are reached at different frequencies for different amplitudes of motion. This will show up as a non-constant phase delay parameter as a function of controller deflection.

Shown here are results of frequency sweeps done at three different amplitudes, indicating that at larger deflections, the apparent phase delay can become significantly larger than at lower deflections. This can come as a surprise to the pilot who had predictable characteristics with smaller deflections.



The final element in the nonlinear control response story is the aerodynamic response to surface deflection. While it is desirable to achieve a linear response to surface deflection, such is simply not always the case.

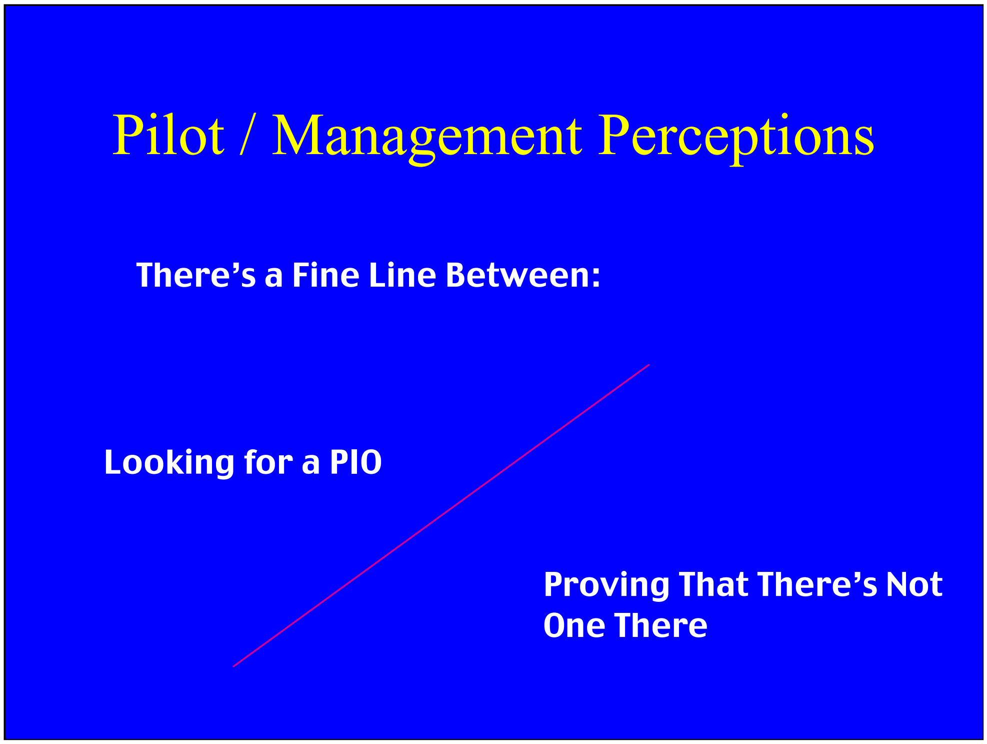
For the same reasons that the control force characteristics produce ambiguity, discontinuities in aerodynamic response do as well. For example, consider a pilot holding a sideslip requiring a surface deflection between the two yellow points. Correction for gusts which may force a deflection which crosses one or both points, will result in the pilot geting less response than was commanded based on the first seen gradient. This lack of predictability can result in loss of precision and frustration on the part of the pilot.



The end result of all of these nonlinear elements is of course that the real airplane is really difficult to analyze with current methods.

Complicating the situation is the fact that pilots, and in particular test pilots, are remarkably adaptable controllers. They may compensate for these elements without being aware that they are, and they may not be able to communicate to the engineer the full consequences of the situation.

Finally, the state of the art in analytical techniques is not felt to be to the point at which these elements can be addressed adequately, and in particular with regard to PIO tendencies.



Ultimately, the pilot is on the spot to pass judgment on PIO tendencies.

Often, the pilot (and sometimes managers who listen to them) will believe that the engineer wants the pilot to induce a PIO. In fact, the engineer usually wants to demonstrate that the pilot will not induce a PIO. The difference between these two situations is often very fine.

In any case, encountering such an event is usually seen as an honest-to-goodness out of control situation, which is generally considered not a good thing. Arriving at an agreed upon set of conditions which will both adequately explore the pilot/vehicle combination and retain adequate safety margins is a very important step in the process.

The Pilot is Part of the Equation

- Pilot “Gain” is Important in Closed Loop Performance and Stability
- Pilot “Gain” is not Easily Controlled
- Standardized Evaluation Tasks will Require a Consistent Level of Pilot Agressiveness

A very important part of the pilot/vehicle combination is of course the pilot himself. An important part of the stability of the combination is the pilot “gain”. Unfortunately, most pilots don’t change their gain at will. A few can increase their gain when asked, but it is rare that a pilot, once in a “high gain” situation can choose to reduce it.

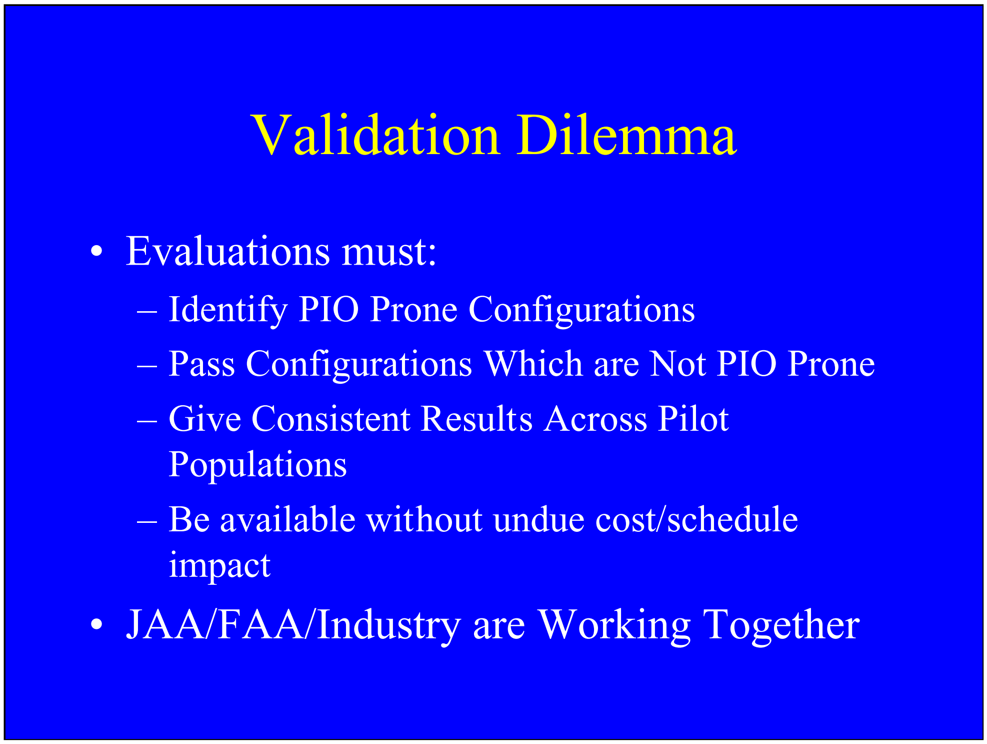
If a standardized evaluation is to take place, there must be a way to normalize pilot aggressiveness across pilots and across individual evaluations. This is essential precisely because of the extreme dependence of the result (PIO or no PIO) on pilot gain.

Techniques to Boost Aggressiveness

- Maneuver Performance Requirements
  - Extreme Precision in Performance
  - Mandatory Control Positions (on stops)
- Urgent Flight Situation
  - Close to the Ground
  - Close to Another Airplane
- Consistency is Difficult to Achieve

Given what was said above about aggressiveness, it should be noted that there are known ways of increasing an individual pilot's gain in a given situation. These include maneuver performance control and control of the urgency of the flight situation.

What remains uncertain, though is a way to achieve consistency. Without that, consistent evaluations will be difficult to achieve.



What can be said about techniques for validating that a configuration is free of PIO tendencies is what an evaluation criterion must do.

Accurate identification of PIO prone configurations is obviously an important characteristic of any evaluation technique.

Equally important is the ability to pass configurations which are not PIO prone. False positives can result in wasted time and energy in identifying unnecessary solutions.

Any proposed evaluation technique must give consistent results across pilot populations so that the results do not depend on which pilot does the evaluation.

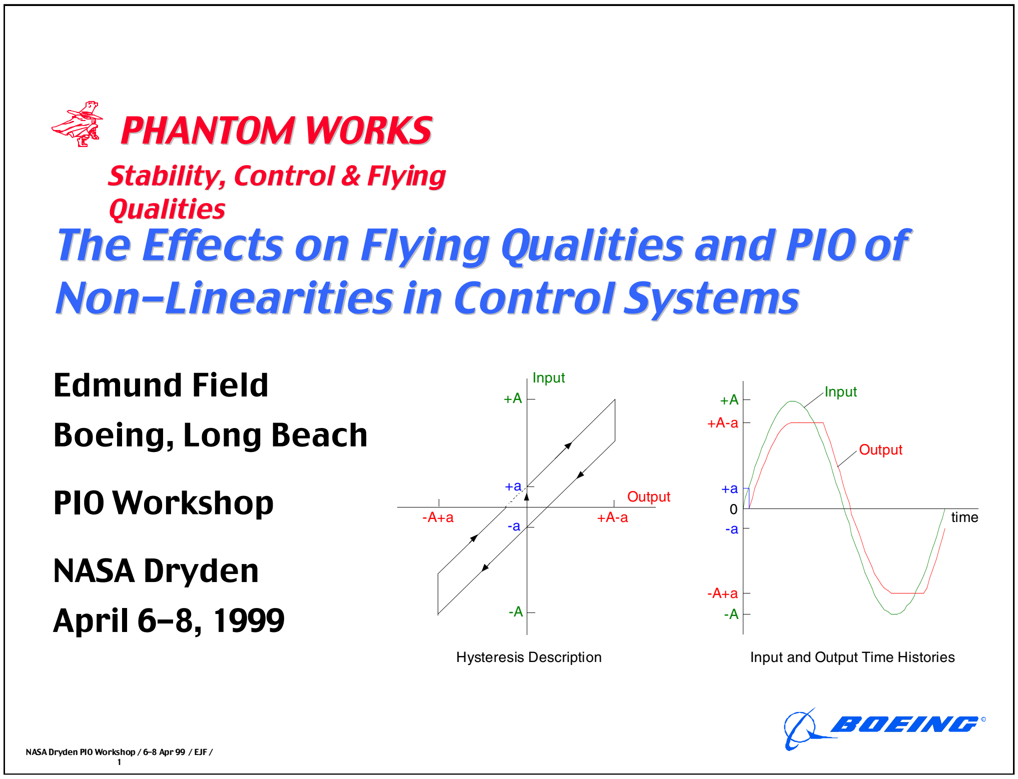
Finally, any evaluation technique should be available without undue cost or schedule impact.

The dilemma is of course that there is no evidence that an evaluation metric is available which meets these criteria.

The good news is that the world's regulatory authorities for transport aircraft are actively working together to monitor the situation and act if appropriate.

Summary

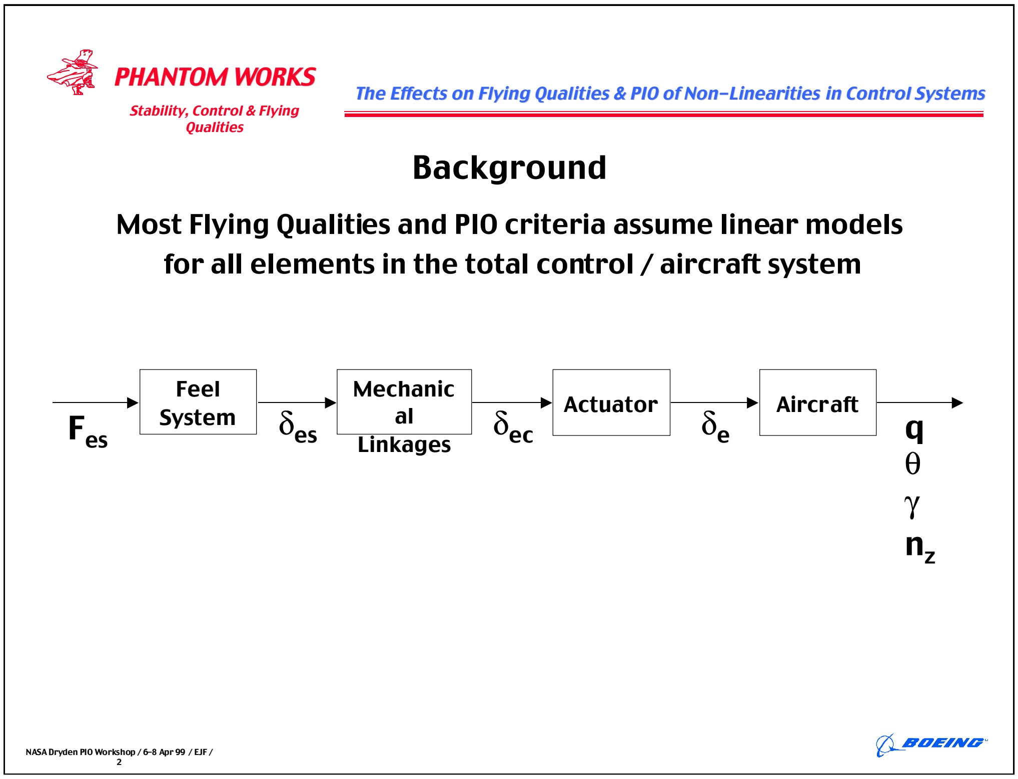
- Boeing's Experience in Testing for PIO is Extensive
  - Generic Testing Program is in Place
  - Database is Being Built / Lessons are Recorded
  - Toolbox is Growing
  - Effective Validation Maneuvers are Elusive
- Many Analysis Details are Available for Consideration
- Most Effective Prevention Strategy is Prudent Handling Qualities Design Practice
- Pilots Are a Key Ingredient: They Must be Involved
- Most Effective Testing Stragegy Appears to be Careful Diligence in Normal Test Flying
- The Process Continues to Evolve



Factors that cause Category I PIOs have received much attention over many years, resulting in the development of many PIO prediction criteria.

More recently attention has turned to Category II PIOs, those that include non-linear effects such as rate limiting. Other sources of non-linearity also exist in an aircraft's control system, however, these have received less attention.

This presentation discusses some recent experience with non-linear elements in control systems, and their implications for flying qualities and PIO susceptibility.



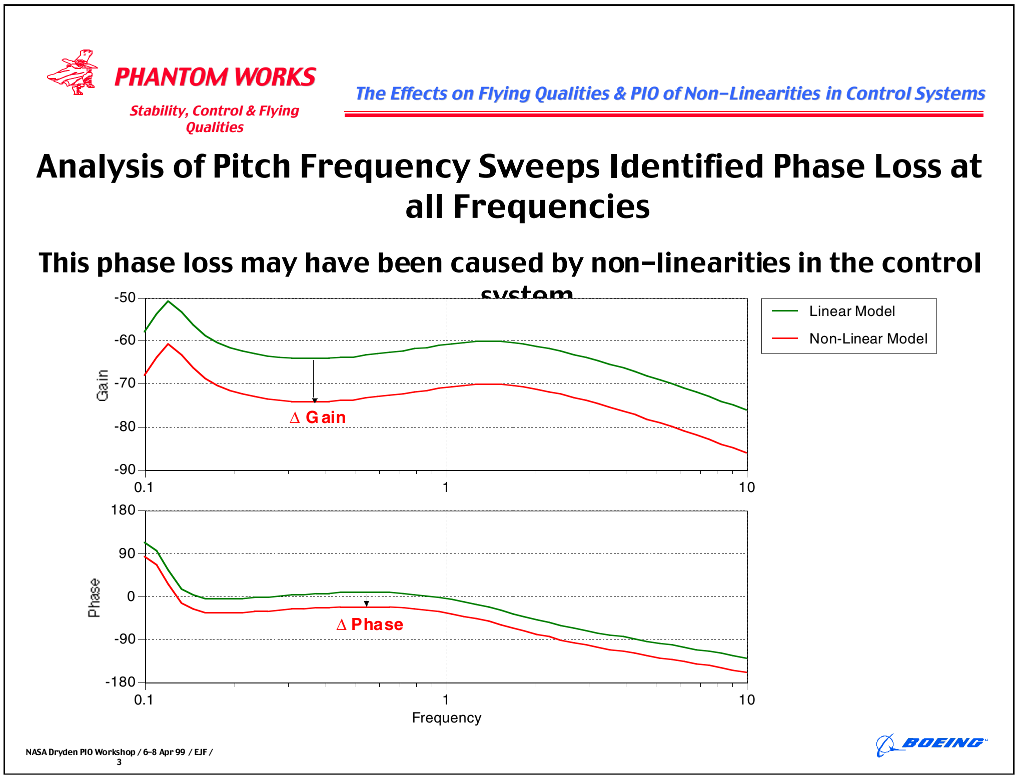
Most flying qualities and PIO prediction criteria assume linear models for all elements in the total control / aircraft system. That includes linear models of the feel system, the mechanical linkages, the actuators and the aircraft dynamics.

Category I PIO criteria concern only linear causes of PIO.

Category II PIO assume non-linearities due to rate limiting only, all other elements in the total control / aircraft system are assumed linear.

While this may be reasonable for a first approximation, in reality all these elements include some non-linearities. The total contribution of all these non-linearities may become appreciable and so have important implications for an aircraft's flying qualities and PIO susceptibility.

For example, hysteresis in the feel system is a well known phenomenon, and yet its effect on an aircraft's flying qualities are neglected when performing linear analyses. To some extent its effects can be neglected if the analyses use control inceptor position (as opposed to force) as the input. However, the effects of the hysteresis should be taken into account elsewhere. Current criteria for this are lacking.



When analyzing data obtained from pilot generated pitch axis frequency sweeps a phase loss was identified at all frequencies in the Bodes of stick force to aircraft response. It was suggested by Mr. Dave Mitchell that this phase loss may have been caused by non-linearities in the control system, specifically hysteresis.

PHANTOM WORKS

Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Categories of Non-Linearities

Input/Output Relationship	Simple	Complex	
Phase Angle	Zero	Non-Zero	
Amplitude Dependent?	Yes	Yes	
Frequency Dependent?	No	No	Yes
Examples:	Friction Threshold Saturation	Hysteresis Toggle Elementary Backlash	Backlash with Coulomb Friction

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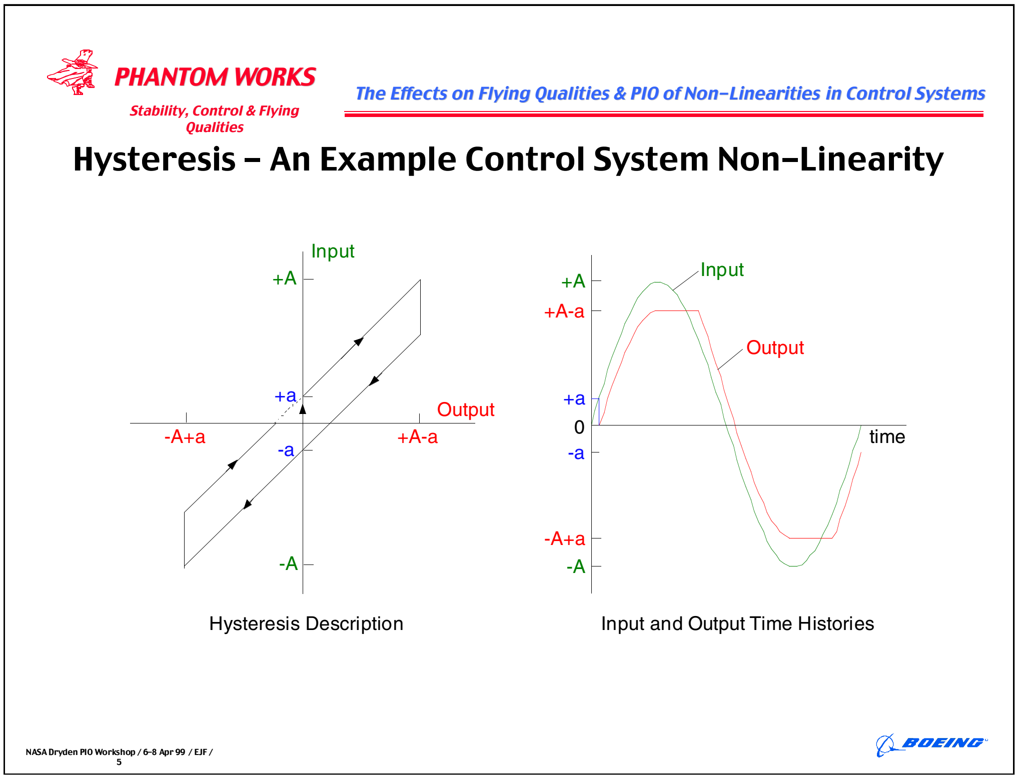
There are several categories of non-linearity that may be present in an aircraft's control system These may be represented by either simple or complex describing functions[1].

Simple non-linearities exhibit gain attenuation, but no phase attenuation. The gain attenuation is independent of the frequency of the input, but dependent upon the magnitude of the input amplitude. Examples include friction, threshold and saturation.

Complex non-linearities exhibit both gain and phase attenuation. The magnitude of the gain attenuation is dependent upon the magnitude of the input amplitude, and may or may not be dependent upon the frequency of the input. Examples of frequency independent complex non-linearities include hysteresis, toggle and elementary backlash. Frequency dependent non-linearities include backlash with Coulomb friction.

Various of these non-linearities may be present in an aircraft's control system. When added together, from the pilot applying a force to the control inceptor to the aircraft responding, there may be appreciable gain and phase attenuation at all frequencies.

1 Graham, Dunstan, and McRuer, Duane, "Analysis of Nonlinear Control Systems", John Wiley and Sons, 1961



Hysteresis is a well known non-linearity which is present in aircraft feel systems. The effects of hysteresis will be discussed as a representative example of control system non-linearities.

Hysteresis is a complex non-linearity which produces gain and phase attenuation independent of the frequency of the input.

In the following discussion the characteristics of hysteresis will be described by the magnitude of the non-linearity ‘a’ and the magnitude of the input signal ‘A’.

The effect of the non-linearity in the time domain is evident in the figure. The magnitude of the output is limited to ‘A-a’, and the output is lagged behind the input, as well as the shape being modified.

The magnitude limiting causes the gain attenuation and the lag provides the phase attenuation that is evident in the Bode plots.

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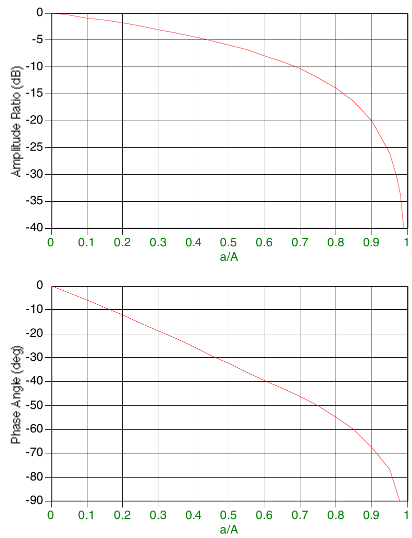
Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Sinusoidal Describing Function for Hysteresis



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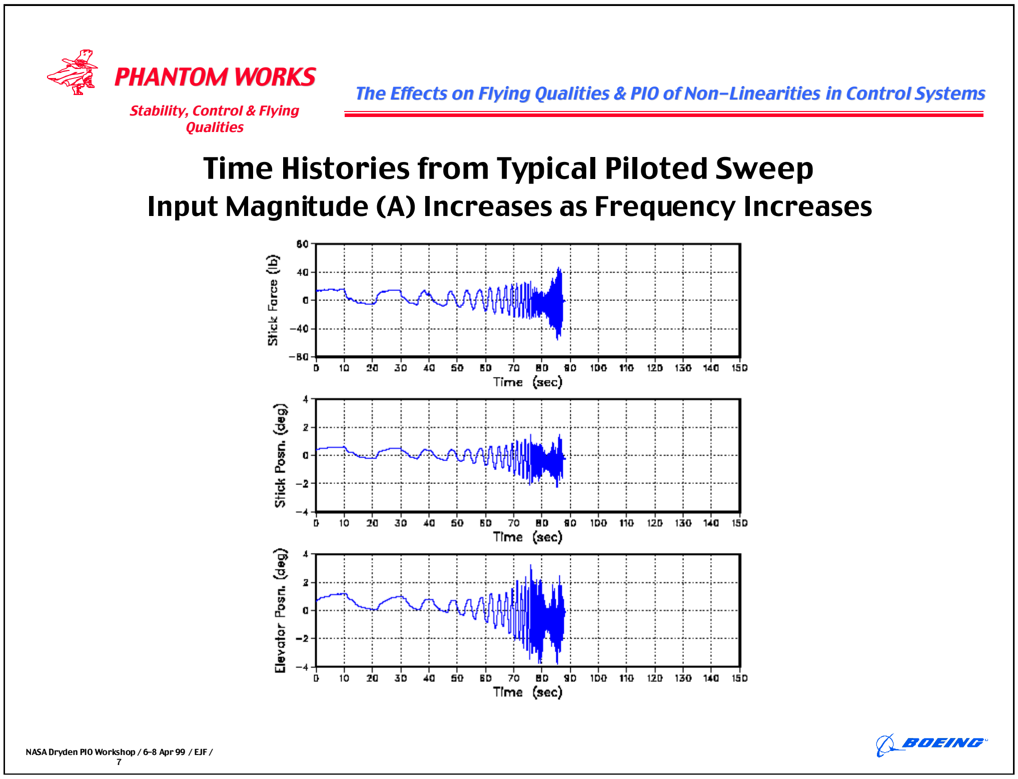
The sinusoidal describing function for hysteresis is shown graphically. The magnitude of the gain and phase attenuation provided by the hysteresis is simply a function of the ratio of the magnitudes of the non-linearity to the input, ‘a/A’.

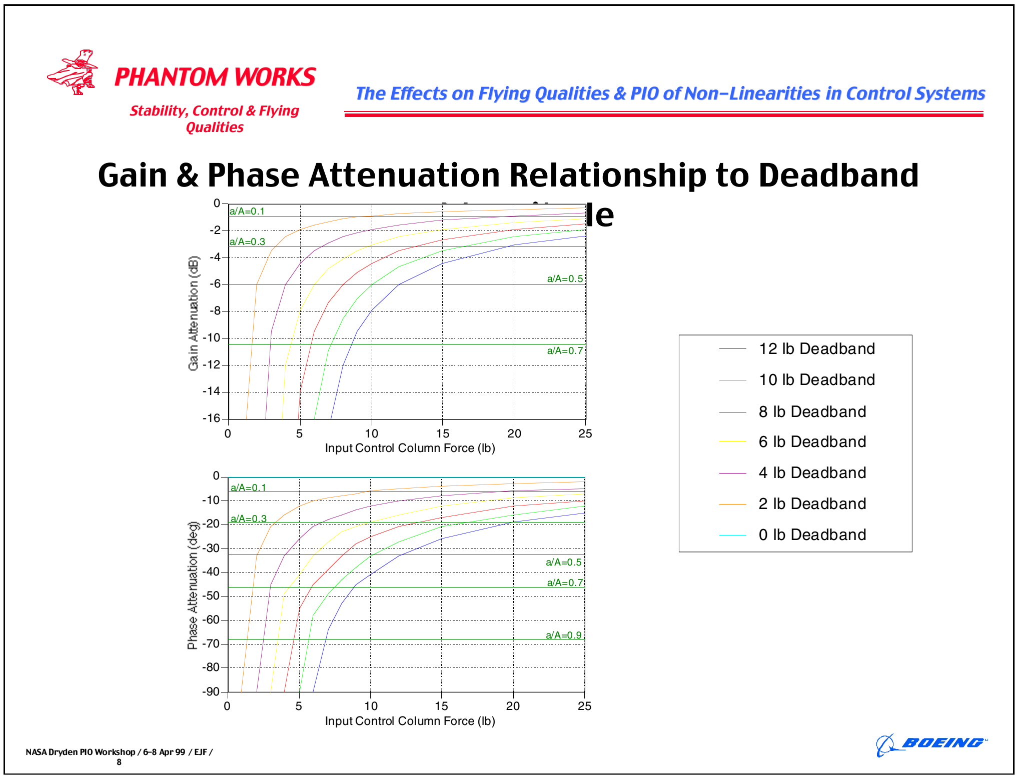
When ‘a/A’ is zero (i.e. zero deadband) there is no gain or phase attenuation. As ‘a/A’ increases both gain and phase loss increase as the effect of part of the applied force is now lost in the deadband zone (-a to +a). As ‘a/A’ increases towards 1 (all applied force is in the deadband region) the gain and phase attenuation approaches infinity, there is no output to the corresponding input.



Although hysteresis is a frequency independent non-linearity, the attenuation it introduces may vary with frequency indirectly.

The figure shows time histories taken from a typical piloted frequency sweep. It can be seen from the figure that as the frequency of the pilot inputs increases the magnitude of the inputs (‘A’) also changes. Generally, as the frequency increases so does the magnitude, although this is not universally true.

The implications for the analysis of frequency sweep data is that the attenuation introduced by any non-linearities may be affected by the frequency/magnitude relationship of the input.



The gain and phase attenuation provided by hysteresis is a function of the magnitudes of the non-linearity ‘a’ and the input sinusoid ‘A’. During a frequency sweep, such as that shown on the previous slide, ‘a’ remains constant, but ‘A’ varies, possibly with frequency. The figures show the variation in gain and phase attenuation with input magnitude ‘A’ for 7 different values of non-linearity ‘a’. Also included are lines of constant ‘a/A’, taken from the slide before the previous .

For a constant deadband ‘a’, as ‘A’ increases ‘a/A’ will reduce. This can be seen by following a line of constant deadband, for instance the solid bold line for a deadband of 8 lb (a = 4 lb either side of trim, to give a total deadband of 8 lb). For low force inputs ‘a/A’ is high, about 0.9 at 4.5 lb. As the magnitude of the inputs increase ‘a/A’ reduces, so that at 6 lb input ‘a/A’ is 0.7, at 8 lb ‘a/A’ is 0.5 and at 13 lb ‘a/A’ is 0.3. As the force increases and ‘a/A’ decreases the curves of constant deadband flatten. The change in gain and phase attenuation with increasing applied force becomes minimal. Physically, this is because the effect of the deadband becomes reduced as the available applied force ‘A-a’ becomes much larger than ‘a’.

The implications for piloted frequency sweep generated data are that the gain and phase attenuation introduced by the non-linearities will be dependent upon the magnitudes of the input, and to some extent will vary with frequency. This makes the prediction of the effects of the non-linearities more difficult.

Implications for Flying Qualities and PIO Susceptibility

- **The phase and gain attenuation introduced by non-linearities in the control system will have implications for the flying qualities and PIO susceptibility of the aircraft**
- **The gain and phase attenuation will be greatest for small control inputs, such as during fine tracking tasks**
- **Non-linearities in aircraft control systems should be minimized to reduce these effects**
- **Caution must be taken when applying flying qualities analyses**

The phase and gain attenuation introduced by non-linearities in the control system will have implications for the flying qualities and PIO susceptibility of the aircraft.

The greatest attenuation will be observed when making small control inputs, such as during fine tracking tasks. Susceptibility to PIO will be greatest for these tasks.

Where possible, the non-linearities in aircraft control systems should be minimized to reduce the attenuation effects they introduce.

When performing flying qualities analyze it is important to appreciate the effects that control systems non-linearities have on an aircraft's flying qualities and PIO susceptibility. Linear analyses that exclude these non-linearities are prone to error, and are likely to predict better flying qualities and lower PIO susceptibility than the real aircraft will exhibit.

PHANTOM WORKS

Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Implications for Flying Qualities Analyses

Aircraft Models:

- **Usually linear models are used. They do not include phase attenuation characteristics of non-linearities**

Flight Data:

- **Complete non-linear aircraft. Data does include phase attenuation characteristics of non-linearities**
- **The effects of the non-linearities dependent upon the magnitude of the control inputs**

Inceptor Force or Position?:

- **Control inceptor force or position can be used as input. Using position avoids the effect of the inceptor hysteresis, a major contributor to the phase attenuation**
- **Elements between the feel system and actuator will be present in both force and position analyses**

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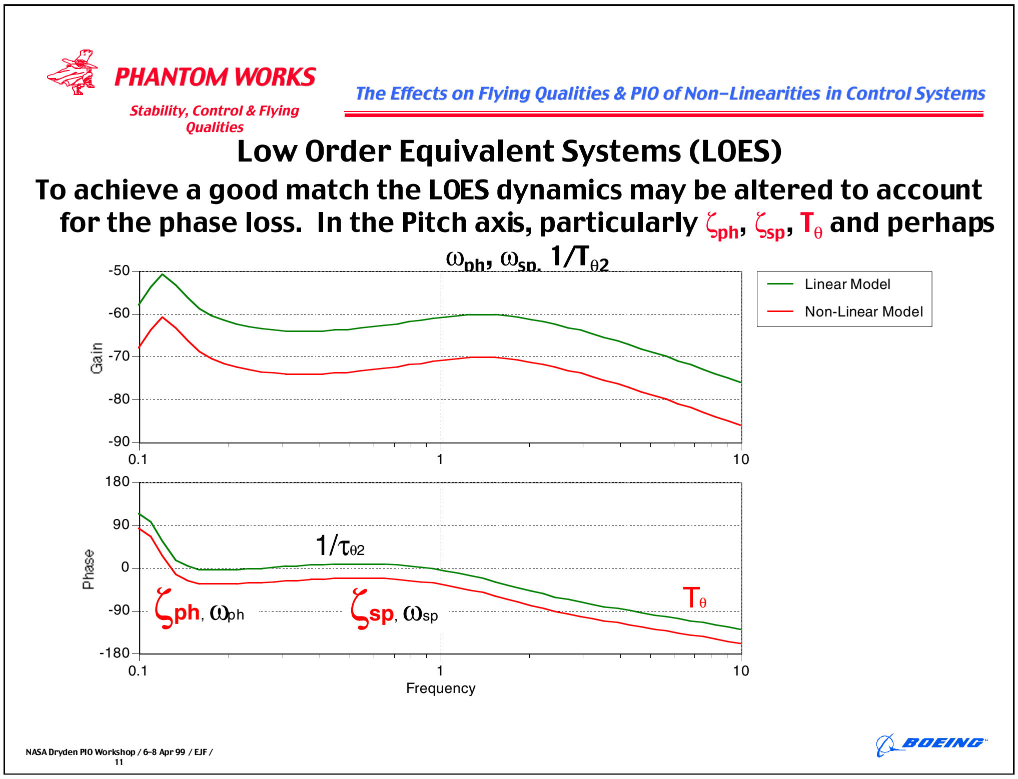
Control system non-linearities introduce several implications for performing flying qualities analyses. It is important that appropriate analyses are performed and that criteria are applied consistently.

When analyzing aircraft models usually only the linear dynamics are considered, and the non-linearities are neglected. Data obtained in-flight represent the total non-linear aircraft. Care must be taken when comparing results from analyses of the linear model and flight derived data. Additionally, data obtained in-flight will be dependent upon the magnitude of the input.

The choice of whether to use stick force or stick position as the input for such analyses will affect the results, since the feel system includes non-linear effects such as hysteresis. Using stick position will limit the included non-linearities.

The implications of analyzing data from the non-linear model (or flight derived data) will be demonstrated against two popular flying qualities analyses:

- Low Order Equivalent Systems
- Bandwidth Criterion



For a constant gain attenuation at all frequencies the only impact on the LOES fit will be a lower gain factor. If the gain attenuation is not constant across all frequencies then the poles and zeros may be affected, possibly resulting in changes to the equivalent short period frequency and damping. Any phase attenuation, regardless of whether frequency dependent or independent, will result in different LOES matches between the linear and non-linear models.

A constant phase loss across all frequencies will likely be matched by an increase in the equivalent damping ratios of the oscillatory modes (ζ_{sp} and ζ_{ph}), spreading the phase reduction across a wider (and so lower) frequency range. If this alone is unable to provide sufficient phase loss it may also be necessary to reduce the equivalent frequency of the oscillatory modes (ω_{sp} and ω_{ph}). Additionally the numerator term $1/T_{\theta 2}$ may also move, partly to offset the movement of the poles. The equivalent time delay term, T_θ, will be adjusted to account for any high frequency offset that is either residual from or caused by the movement of the poles and zeros. Note also that T_θ will also be affected if there is any frequency dependent gain attenuation that causes movement of the poles and zeros.

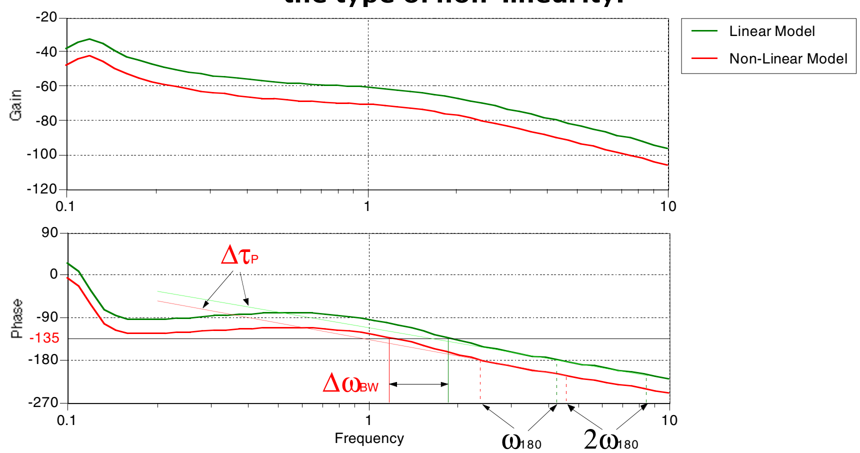
ω_{sp} and $1/T_{\theta 2}$, are both factors in CAP. A PIO prediction criterion based upon CAP and T_θ has been proposed. Clearly, any inaccuracies in the prediction of these parameters will affect the prediction of an aircraft's susceptibility to PIO. The likely effect of hysteresis is to increase an aircraft's PIO susceptibility.

PHANTOM WORKS
Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Bandwidth Criterion

To account for the phase loss the Bandwidth frequencies (both attitude and flight path) will be reduced. τ_p may be affected, depending upon the type of non-linearity.



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As with LOES, a constant gain attenuation at all frequencies will not affect the Bandwidth criterion parameters. Even if the gain attenuation is frequency dependent it is unlikely to affect the Bandwidth criterion parameters since most aircraft are phase Bandwidth limited, and whatever causes the gain response to attenuate is likely to have a greater effect on the phase response.

Any downward shift of the phase response will have a direct effect on the Bandwidth frequency, reducing it by $\Delta\omega_{BW}$. Since τ_P is proportional to the slope of the phase curve between ω_{180} and $2\omega_{180}$ it will be affected slightly by a downward shift in the phase response, as can be seen in the figure. However, τ_P may be affected even more if the slope of the phase response is dramatically different between the ω_{180} and $2\omega_{180}$ frequencies of the linear and non-linear models.

ω_{BW} and τ_P are variables in a proposed PIO prediction criterion. Clearly their accurate definition is important if the PIO prediction criterion is to be valid. As with LOES, the omission of non-linearities from the analysis is likely to predict the aircraft less PIO susceptible than it really is.

PHANTOM WORKS

Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Conclusions

- Non-Linearities in control systems can introduce gain and phase attenuation
- Depending upon the type of non-linearity, the attenuation may be frequency and / or input magnitude dependent
- FQ analyses performed with and without the non-linearities will yield different results
- This may account for inconsistent predictions from flying qualities analyses of linear and non-linear models and flight data, and when including and excluding the feel system

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PHANTOM WORKS

Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Recommendations

- Non-Linearities in control systems must always be considered when addressing an aircraft's flying qualities
- This might be achieved through the development of a criterion accounting for all non-linearities in a control system. This metric might be additive to existing criteria

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BOEING

Mitigating the APC Threat - a work in progress

Ralph A'Harrah

APC Workshop
DFRC
6-8 April 1999

My Perspective

- **What I would do** if I was responsible for
  - Research
  - Design & Development
  - Flight Test
  - Certification
  - Airline Safety
  - Accident Investigation

… relative to mitigating the APC threat

2

Mitigating the APC Threat -

Cat. II APC Research

- **Task Identification**
  - e.g., a large ("over driving") correction to an upset, followed by closed-loop control to get back on original flight path
- **Subject Identification**
  - e.g., APC evaluation results from naïve "line" pilots compared with experienced test pilots
- **Vehicle Identification**
  - Variable stability aircraft, or ground based flight simulator, or actual aircraft

continues

2

Mitigating the APC Threat -

Cat. II APC Research , continued

- Design and demonstrate a control system that is free from Cat. II APC characteristics for a wide range of surface rate limits (e.g., from 1% to 100% of the maximum achievable surface rate)

3

Mitigating the APC Threat -

Design & Development

- **Incorporate favorite PIO criteria into Mark Tischler's Conduit* Program to address Cat. I**
- **Minimize the actuator energy metric (cost function) in Conduit (Con**trol **D**esigner's **U**nified **Int**erface)
  - to reduce probability of "over driving" beyond rate limits, a Cat. II condition
  - to increase actuator life
- **Utilize tactile control feedback[1] on primary controls to warn of approach to rate and/or position limiting, with active stops to preclude "over driving"**

continues

[1]analogous to NRC's collective limit cueing, AvWk, p.53, 22Feb99

3

Mitigating the APC Threat -

Design & Development, continued

- Backup tactile control feedback on primary controls design with adaptive filtering[1,2] to compensate for time delay caused by "over driving"
- Isolate pilot controlled surfaces and actuators from non-pilot controlled surfaces and actuators
  - Reduce erosion of pilot control response and authority from non-piloted intrusion

[1]Hanke, Dietrich, Phase compensation: a means of preventing APC caused by rate limiting, Forschungbericht 98-15

[2]Runqudqwist, Lars, Phase compensation of rate limiters in JAS-39 Grippen, AIAA Paper 96-3368

4

Mitigating the APC Threat -

Ground/Flight Test

- From ground calibration tests, determine the cockpit controls to surface response time delay and hysteresis characteristics for inputs up to the maximum input rate & deflection capability of the pilot
- If values exceed expectations /guidance /specifications, evaluate options for improvement
- Alternately, evaluate on variable stability aircraft while performing off-set landing, large upset correction, etc., Cat. 2 APC maneuvers to define criticality of the problem

Note: The issue here is the consistent ability of line pilots to accommodate the change in time delay and hysteresis characteristics that may be experienced as part of a "hair raising" experience such as a large upset, or an eminent inflight

4

Mitigating the APC Threat -

Certification

- Continue APC exposure/training of certification pilots, using a variable stability aircraft
- Emphasize the determination of evaluation tasks for Cat. II APC that are both safe and effective
- Evaluate in flight APC Cat. I characteristics using existing FAA APC testing bench mark tasks
- Would not attempt Cat. II in-flight evaluation until safe and effective test technique is identified

continues

5

Mitigating the APC Threat -

Certification, continued

- From ground calibration tests, determine the cockpit controls to surface response time delay and hysteresis characteristics for inputs up to the maximum input rate & deflection capability of the pilot

continues

Mitigating the APC Threat -

Certification, continued

- If time delay or hysteresis values exceed expectations /guidance /specifications, evaluate on variable stability aircraft while performing off-set landing, large upset correction, etc., Cat. 2 APC maneuvers

Note: The issue here is the consistent ability of line pilots to accommodate the change in time delay and hysteresis characteristics that may be experienced as part of a "hair raising" experience

Mitigating the APC Threat -

Airline Safety

- For the cockpit primary control inputs and the resulting control surface outputs, record at data rates of 20 Hz or greater on the QAR
- Initial APC Precursor
  - Monitor QAR data for the time lapse between reversal of the cockpit control rate and the associated reversal of the surface rate as APC precursor
    - Flag occurrences with $t_D > 100$ msec.
    - Flag & record values of t_D when $t_D > 150$ msec.
- Involve APC specialist for consistent flags, or values of $t_D > 150$ msec.

continues

6

Mitigating the APC Threat -

Airline Safety

- Growth APC Precursor
  - Utilize 20 Hz. or greater data rates on primary controls, primary control surfaces, aircraft accelerations, and warning, such as "stall" and "over-speed"
  - Utilize QAR data to support Conduit as a monitor
    - Flag occurrences violating Level 1 criteria.
    - Flag & record values of t_D when $t_D > 150$ msec., and Level 2 criteria.
    - Involve APC specialist for consistent flags, or values of $t_D > 150$ msec

7

Mitigating the APC Threat -

Accident Investigation

- For the primary cockpit flight controls, the associated control surfaces, and aircraft accelerations felt by the pilots, require that crash recorders utilize data rates of 20 Hz or greater
  - when the flight crew is actively involved with primary flight controls
  - when an emergency has been declared

continues

7

Mitigating the APC Threat -

Accident Investigation, continued

- In an investigation exhibiting significant crew control activity, examine the time lapse between cockpit control inputs, the associated control surface responses, and accelerations (or other response metrics, such as warnings) to which the pilot may be responding
- If the time lapse exceeds 100-150 msec., include a team of APC specialists as part of the investigative team

8

Session IV

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FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS

- **APC TENDENCIES HIGHLIGHTING : MANEUVERS DESCRIPTION**
  - SYSTEMATIC MANEUVERS
  - NON SYSTEMATIC MANEUVERS
- **NEW TOOLS TO INCREASE MANEUVERS ACCURACY**

FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS

APC = PILOT HIGH GAIN

- UNEXPERIENCED PILOTS
- STRESSFUL ENVIRONMENT:
  - final approach
  - formation flight
  - workload
- CAPTURE AND FINE TRACK ING TASKS:
  - altitude
  - heading
  - speed
  - roll
  - yaw

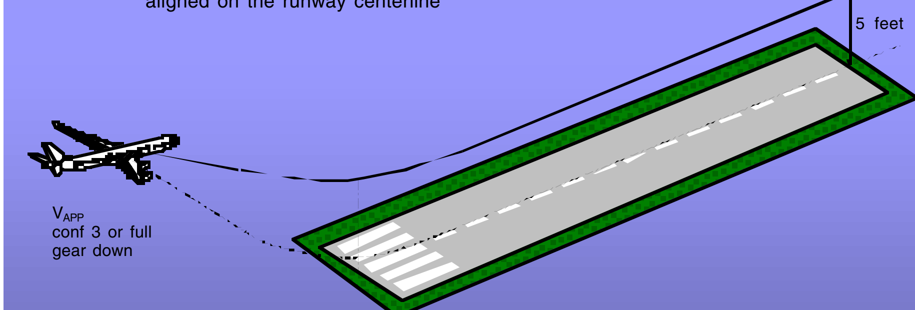
 page3 April 1999

FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS

SYSTEMATIC MANEUVERS

RUNWAY FLY OVER:

The pilot must maintain a constant altitude and airspeed, and the aircraft aligned on the runway centerline



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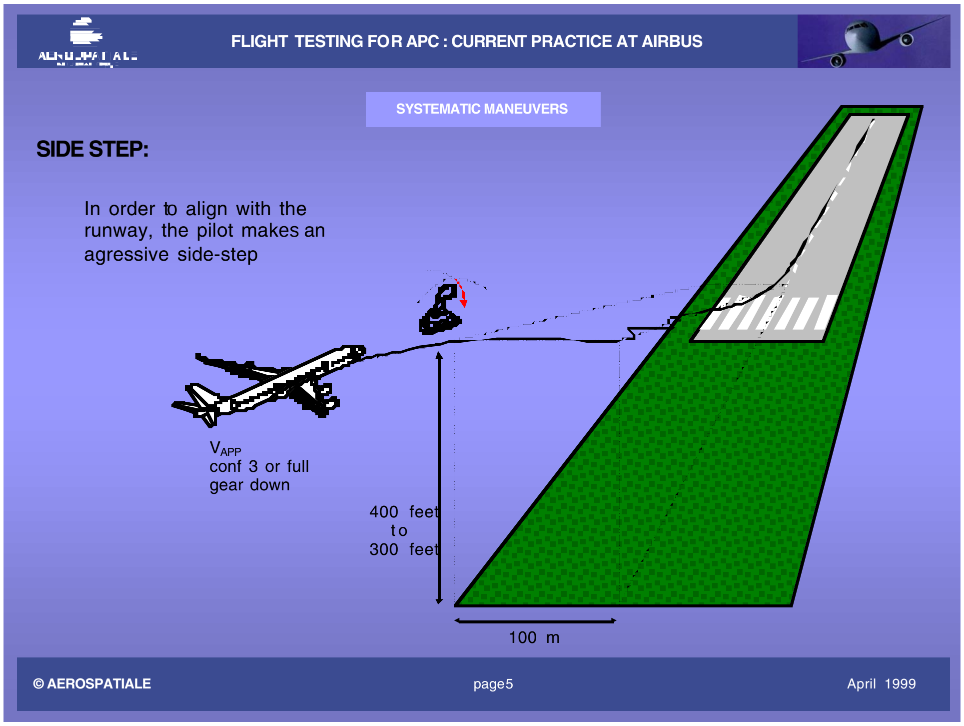
FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS
SYSTEMATIC MANEUVERS
SIDE STEP:
In order to align with the runway, the pilot makes an agressive side-step
V APP
conf 3 or full
gear down
400 feet
to
300 feet
100 m
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page5
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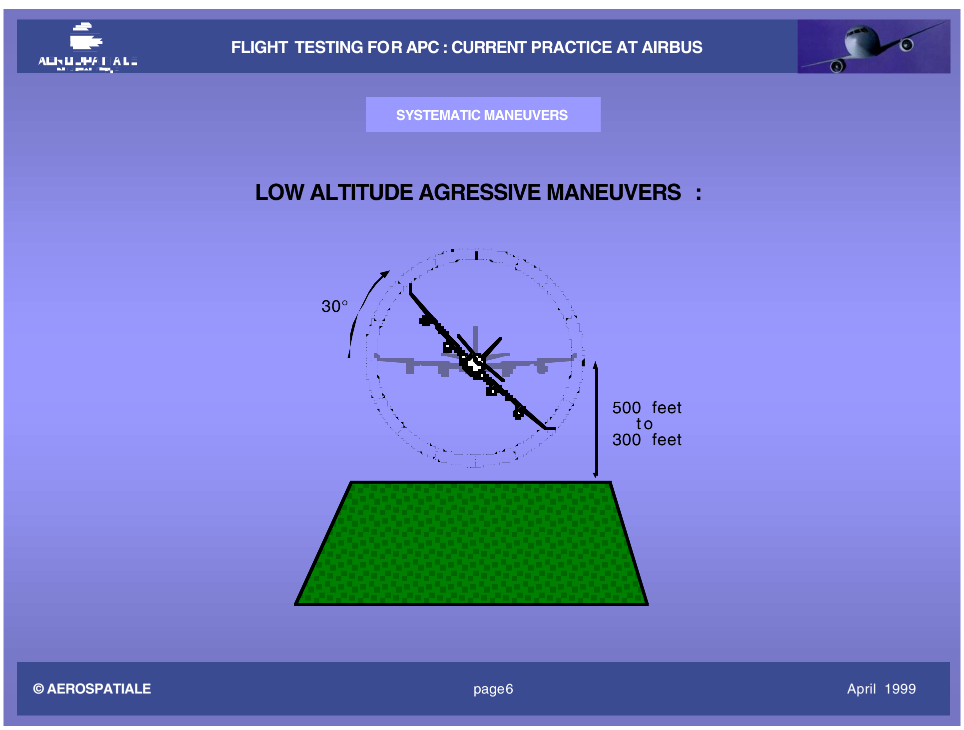
FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS
SYSTEMATIC MANEUVERS
LOW ALTITUDE AGRESSIVE MANEUVERS :
30°
500 feet
to
300 feet
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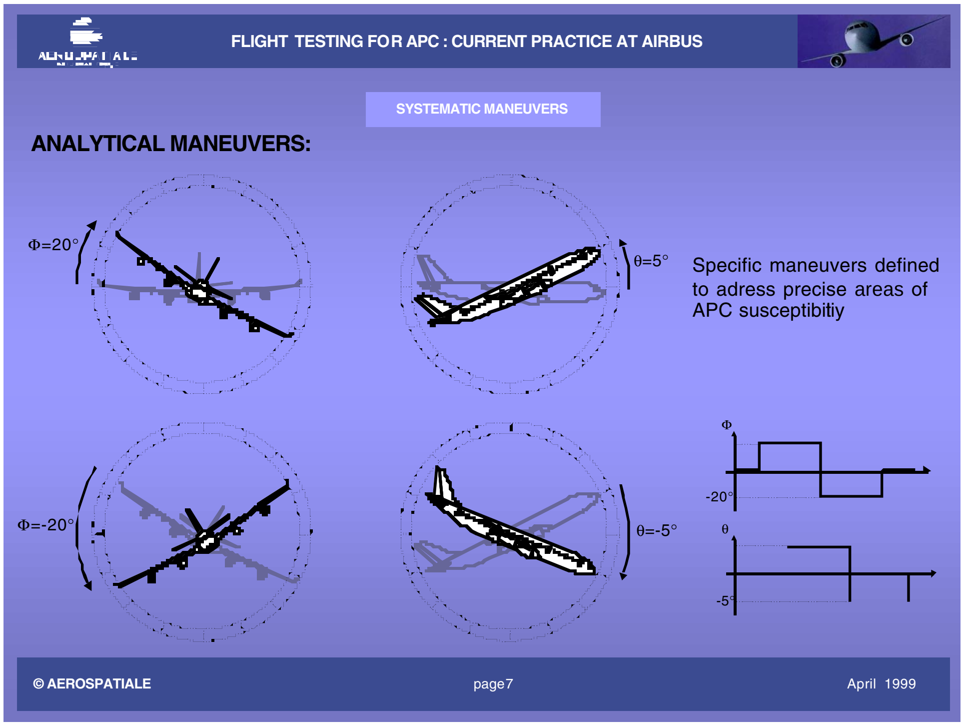
FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS
SYSTEMATIC MANEUVERS
ANALYTICAL MANEUVERS:
Φ=20°
θ=5°
Φ=-20°
θ=-5°
Specific maneuvers defined to adress precise areas of APC susceptibitiy
Φ
-20°
θ
-5°
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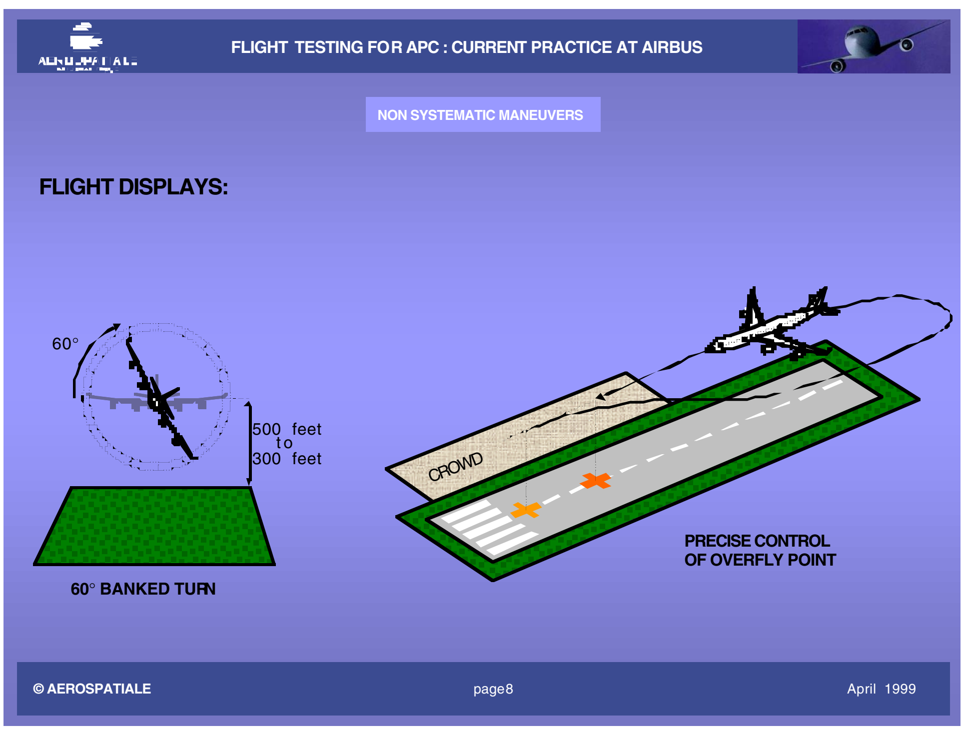
FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS
NON SYSTEMATIC MANEUVERS
FLIGHT DISPLAYS:
60°
500 feet
to
300 feet
60° BANKED TURN
CROWD
PRECISE CONTROL
OF OVERFLY POINT
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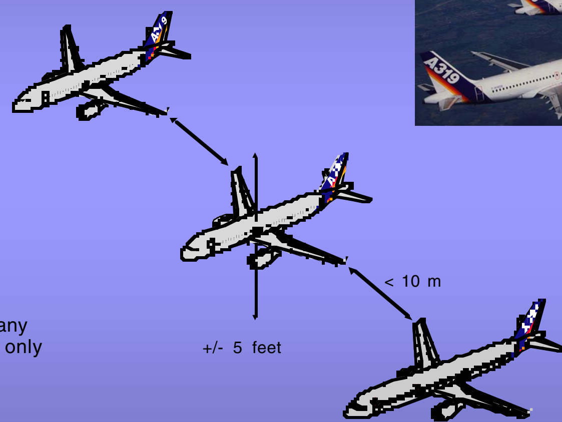
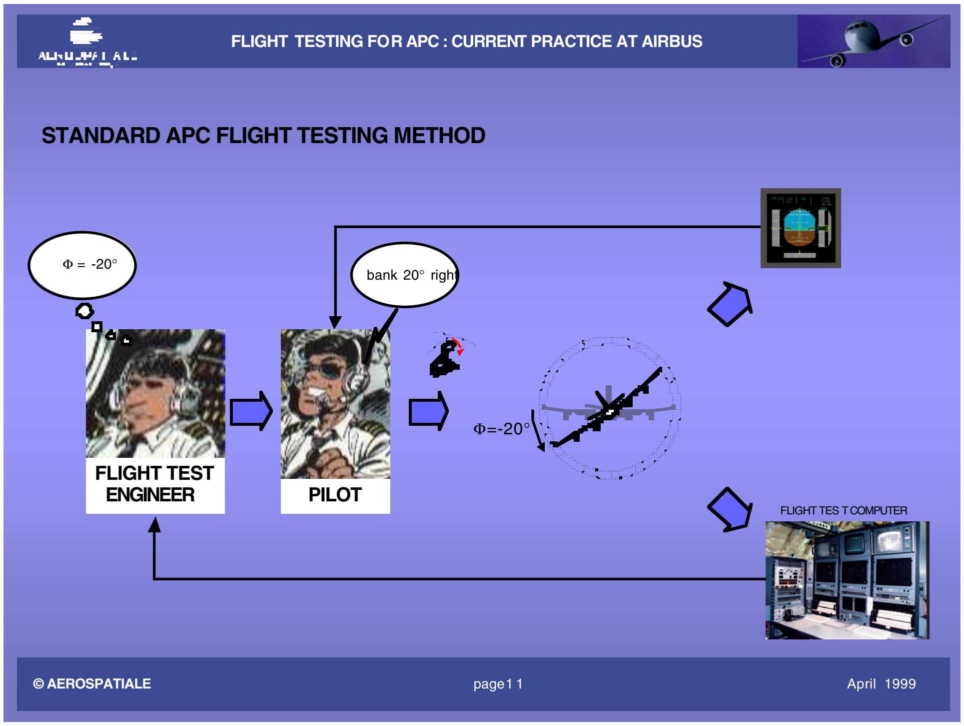
NON SYSTEMATIC MANEUVERS

FORMATION FLIGHT:

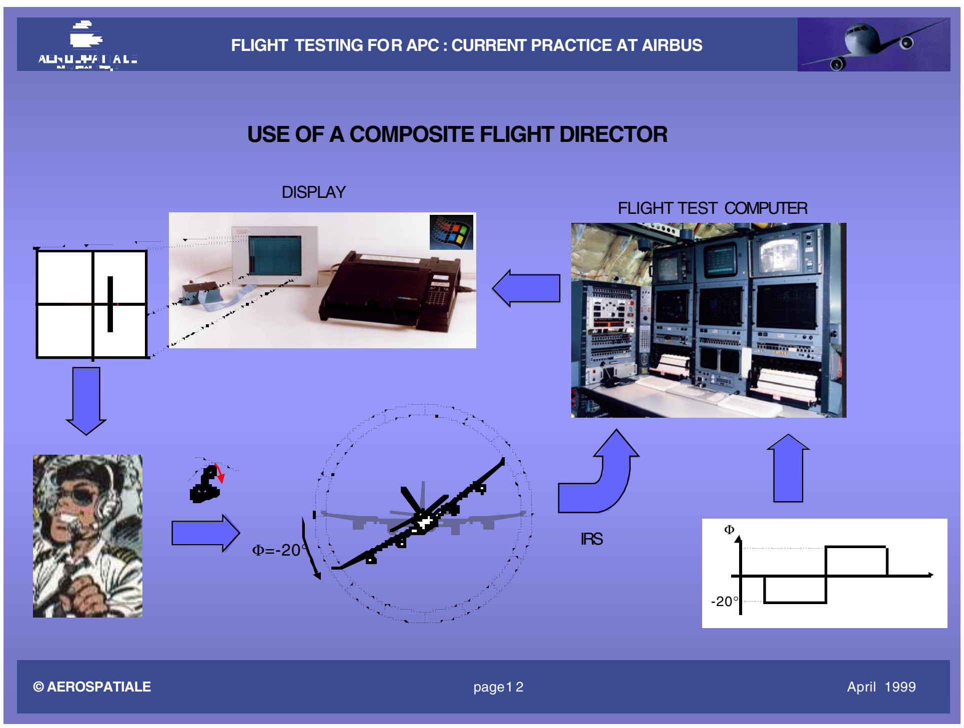


Can be performed in many configurations, and not only in approach

- APC TENDENCIES HIGHLIGHTING : MANEUVERS DESCRIPTION
- **NEW TOOLS TO INCREASE MANEUVERS ACCURACY**



FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS
STANDARD APC FLIGHT TESTING METHOD
Φ = -20°
bank 20° right
FLIGHT TEST ENGINEER
PILOT
Φ=-20°
FLIGHT TES T COMPUTER
© AEROSPATIALE
page1 1
April 1999



FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS
USE OF A COMPOSITE FLIGHT DIRECTOR
DISPLAY
FLIGHT TEST COMPUTER
Φ=-20
IRS
Φ
-20°
© AEROSPATIALE
page1 2
April 1999

COMPOSITE FLIGHT DIRECTOR ALLOWS ACCURATE MANEUVE RS :

- both FD bars show θ and Φ distance to targets
- enable any complex target (ramp, multi-sinusoid, pseudo random,...)
- provide a wide range of analytical maneuvers

- *cannot autoadapt (like a flight test engineer would do to trap the pilot)*

FLEXIBLE TOOLS :

- display delay can be adjusted
- FD bars can provide composite displays (use of many feedbacks n_Z, n_Y, q,..)

APC MARGIN SETTING

LESS PILOT GAIN NEEDED FOR AP C TESTING

The Prediction and Suppression of PIO Susceptibility of Large Transport Aircraft

- An Evaluation of Proposed Methods -

Rogier van der Weerd
Delft University of Technology / Aerospace Engineering
Department of Control and Simulation
6 April 1999

Prepared and presented by

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This presentation is based on the results of a study more thoroughly reported in:

Weerd, van der R.; 'PIO Suppression Methods and Their Effects on Large Transport Aircraft Handling Qualities'; Thesis (M.Sc.), Delft University of Technology, Delft (The Netherlands), January 1999

The study was carried out under a cooperative agreement between Delft University of Technology in the Netherlands and The Boeing Company at Long Beach. A student placement was made possible at the Stability, Control and Flying Qualities group of Boeing Phantom Works.

The project was carried out under supervision of:

The Boeing Company	Delft University of Technology
John Hodgkinson	Prof.dr.ir. J.A. (Bob) Mulder
Dr. Edmund J. Field	ir. Samir Bennani
Walter von Klein Jr.	

CONTROL & SIMULATION

Contents

The study into PIO had two main objectives:

1. Investigate available methods for PIO prediction, including those recently proposed
2. Investigate possible remedies to PIO

Some of the group's expertise and experience with PIO could be used to evaluate and validate different criteria and methods using an example large transport aircraft with different configurations that have handling qualities that are considered well understood / investigated.

Prediction of PIO

3

<u>Limitations of Linear Methods (Category I)</u>

Most observed PIOs involved rate saturation of control surface actuator(s)

- Rate Saturation Result of PIO (poor Cat I properties)
- Or, Rate Saturation Actual Cause of PIO ?

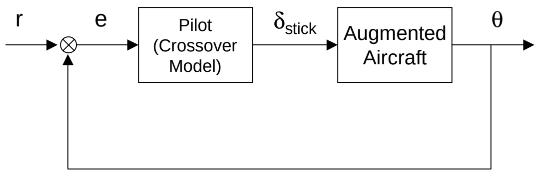
Cat II Evaluation requires the inclusion of nonlinear behavior

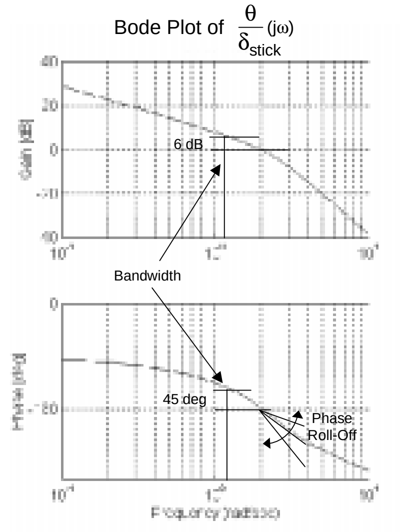
This can be done in

- Time Domain
  - Time Domain Neal-Smith
  - Hess Method for Nonlinear Dynamics
- Frequency Domain Using Describing Function Technique
  - DLR’s Open Loop Onset Point (OLOP)

Prediction of PIO
Category I Example - Bandwidth

4





<u>Two Important Parameters</u>

- Bandwidth Frequency, ω_{BW}
  (“Speed” of System)
- Phase Roll-Off, τ_p
  (“Predictability”)

The Bandwidth criterion has been shown to be a well performing criterion on a wide variety of cases.

Extending Bandwidth to systems with nonlinear elements is possible (in fact, the method of performing a frequency sweep in order to estimate the system frequency response includes all kinds of nonlinear elements of the real system). Rate limiting elements in the command path of the EFCS can be identified easily for a given input amplitude. However, if the rate limiting element is part of a feedback loop, the identification of the describing function may fail, as typical nonlinear system behavior gets into play, e.g. the introduction of multiple equilibria (limit cycles, jump resonance).

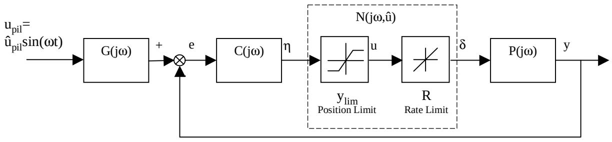
REF

Hoh et al 1982.

Mitchell et al 1994

Mitchell et al 1998

Nonlinear Systems (i)



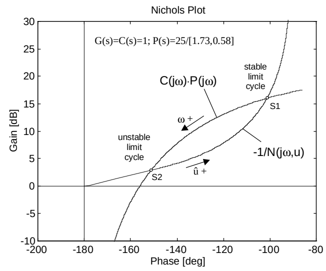
Limit Cycles - sustained nonlinear oscillations, fixed amplitude, fixed frequency

Conditions for a Limit Cycle are sought

Use neutral stability condition (Popov):

$$C(j\omega)\cdot N(j\omega,\hat{u})\cdot P(j\omega) = -1$$

$$\Rightarrow \quad C(j\omega)\cdot P(j\omega) = -\frac{1}{N(j\omega,\hat{u})}$$



N(jω,û) is the sinusoidal describing function represenation

Nonlinear Systems (ii)

Jump Resonance

No unique relation anymore between frequency and gain/phase of closed-loop response

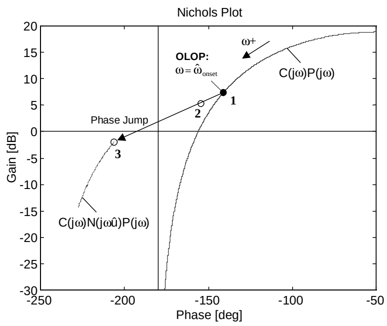
Phase Jump in Pilot-Vehicle System

⇩

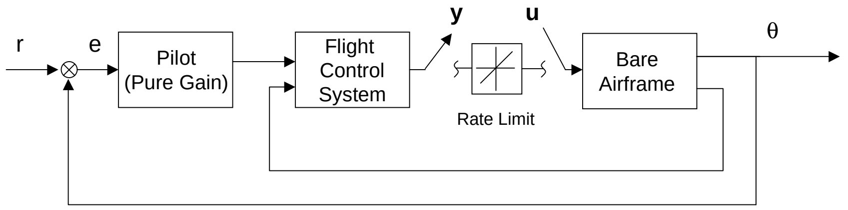
Misadaptation by Pilot

⇩

PIO

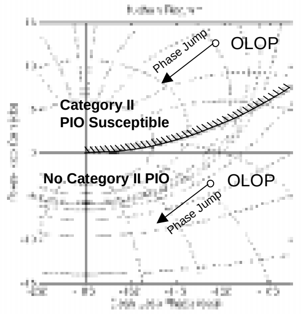


Prediction of PIO
Category II Example - OLOP



Rate limiting causes Jump Resonance
OLOP determines "the consequence".

OLOP is $L(j\omega) = \frac{Y}{U}(j\omega_{onset})$
At the onset frequency



REF

Duda 1997

Duda et al 1997

Case Study Configurations Of The Example Aircraft

8

- Receiver Aerial Refueling Task
  - Clean Configuration
  - High Speed, $M = 0.613$
  - High Altitude, $h = 20{,}000$ ft
- Pitch Rate Command System Configurations:
  - Old Software Version F → PIO PRONE
  - Updated Software Version H → PIO FREE
    Added Phase Lags τ_l=[0.1,0.25]
- Simplifications
  - Single Axis
  - No Model Uncertainties
  - No Structural Dynamics

The Example Aircraft

High Performance Fly-By-Wire Military Cargo Airplane.

High-wing, four engines, T-tail configuration. Length 175 ft, height 55 ft, wingspan 170 ft, MTOW 600,000 lbs

'High gain' mission tasks include: Landing/Takeoff Short Austere Airfields and Aerial Receiver Refueling. PIOs were encountered during developmental flight testing for both tasks [1],[2]

Configurations

Apart from configurations representing old and updated Electronic Flight Control System (EFCS) software versions, additional configurations were evaluated that represent the updated EFCS software with intentionally deteriorated characteristics.

The latter is accomplished by adding phase lags in the flight control system by increasing the time constant of a first order filter residing in the command path of the control laws.

REF

Iloputaife et al 1996

Iloputaife 1997

Pitch Axis PIO Event
EFCS Software Version F

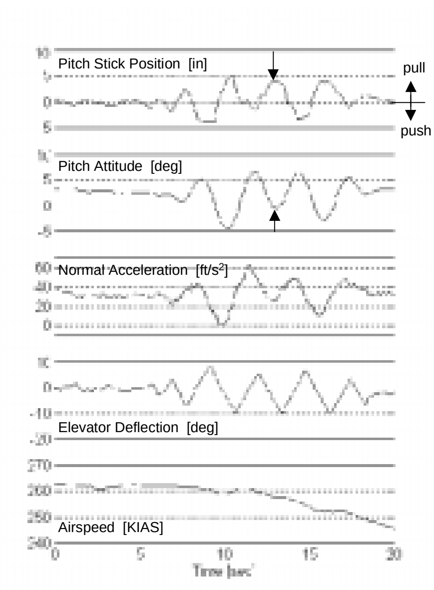
9

Pilot initiated emergency breakaway from tanker

Typical category II PIO:

- "High pilot gain"
- "Pilot is 180° out of phase" with pitch attitude
- Software rate limiting of elevator command signal

[Ref. Iloputaife 1997, Iloputaife et al 1996]



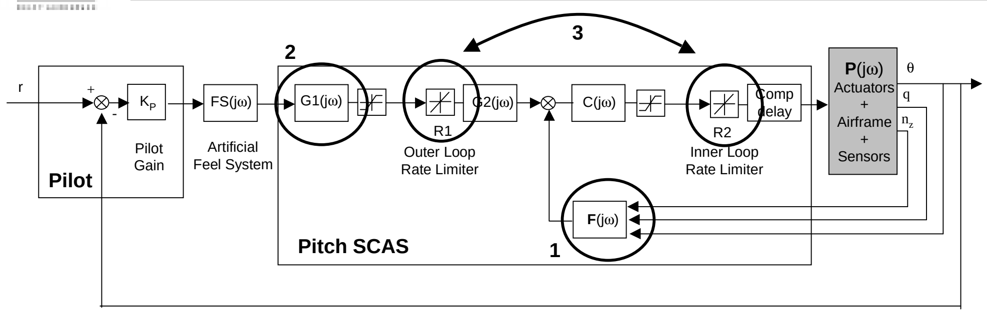
REF

Iloputaife et al 1996

Iloputaife 1997

Example Aircraft Control Law Changes

10



Main differences between old and new software

1. Structural filtering optimization → increase system bandwidth
2. Stick shaping change → reduce control sensitivity
3. Change rate limits → fully use actuator capability

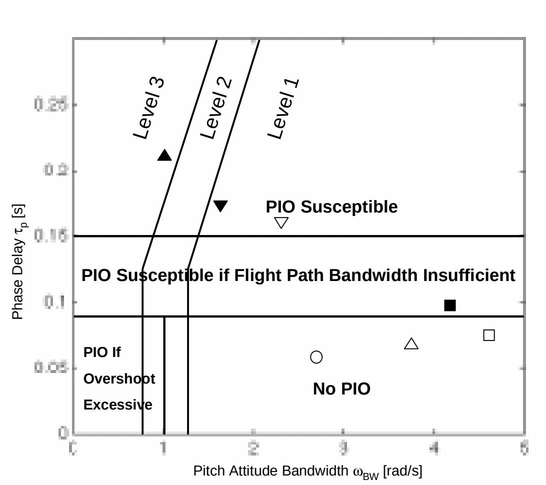
[Ref.Iloputaife 1997,Iloputaife et al 1996]

REF

Iloputaife et al 1996

Iloputaife 1997

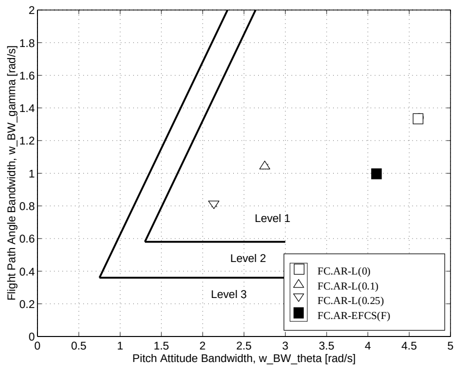
Bandwidth Criterion
Validation Using Example Aircraft



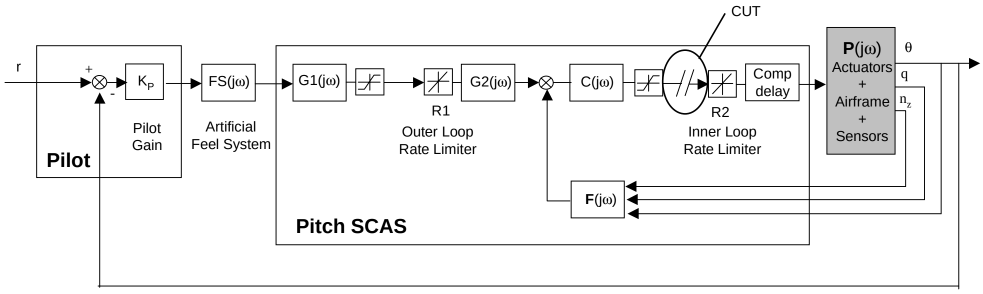
▲	PIO	**B-2** * Approach	Flight Test
△	No PIO	**B-2** * Aerial Refueling	Flight Test
▼	PIO	**Space Shuttle** *	Flight Test
▽	No PIO		
○	No PIO	**X-15** *	Flight Test
■	PIO	**Example Aircraft**	Flight Test
□	No PIO		

* Source: Klyde, D.H. et al 1995

Criterion mapping is not considered to be successful discrimination since flight path bandwidth is sufficient for both configurations



OLOP Criterion
Application to Example Aircraft



1. Assume pure gain pilot that exerts sinusoidal stick signal with certain amplitude |r|
2. Determine the onset frequencies of all rate limiting elements using

$$\hat{\eta}2(\omega, \hat{u}_{pil}) = \frac{R}{\omega_{onset}}$$

$$\hat{\eta}2(\omega, \hat{u}_{pil}) = \left|\frac{\eta 2}{u_{pil}}(j\omega_{onset,N2})\right| \cdot \hat{u}_{pil} = \left|\frac{G1 \cdot G2 \cdot C(j\omega_{onset,N2})}{1 + C \cdot P \cdot F(j\omega_{onset,N2})}\right| \cdot \hat{u}_{pil}$$

This equation can be solved graphically

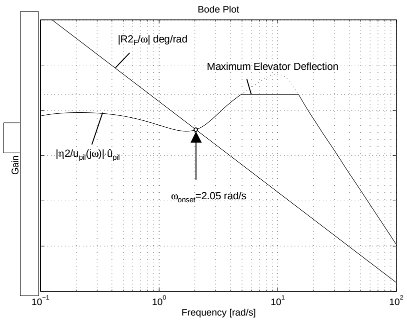
3. At the critical rate limiter, cut loop, plot loop transfer function on Nichols Chart
4. OLOP is point on locus for $\omega = \omega_{Onset}$. Its position can be related to Category II PIO susceptibility

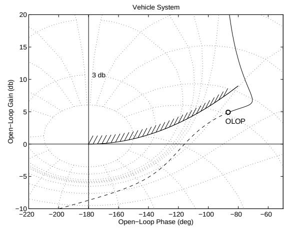
OLOP Criterion
EFCS Software Version F (old)

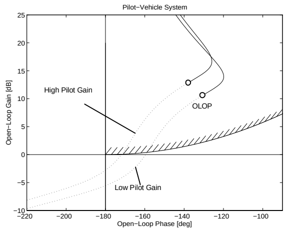
Onset Frequencies

Inner-Loop ω_{onset}=2.05 rad/s

Outer-Loop ω_{onset}=3.53 rad/s

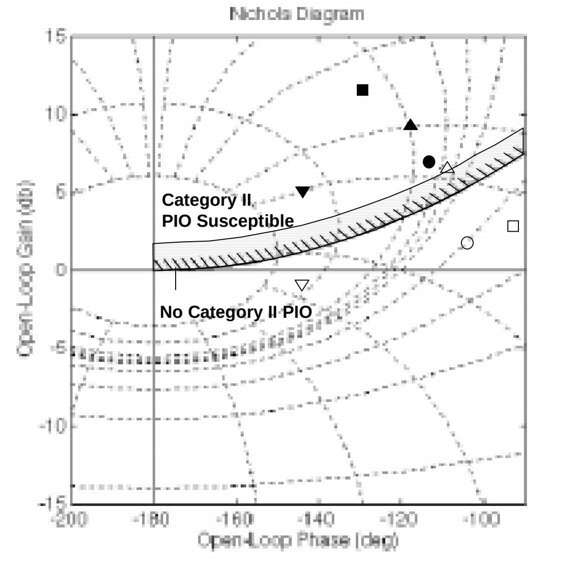






OLOP Criterion
Validation Using Example Aircraft

14



▲	PIO	**Saab** * In-Flight Sim Experiment
△	No PIO	
▼	PIO	**Space Shuttle** * Flight Test
▽	No PIO	
●	PIO	**F-18** * Flight Test
○	No PIO	
■	PIO	**Example Aircraft** Flight Test
□	No PIO	

* Source: Duda, H. 1997

Results Comprehensive Criteria Validation

Results Category I Criteria

	LOES CAP	LOES τ_e	Bandwidth	Gibson	Smith-Geddes	Hess	Neal-Smith
FC.EFCS(F)	**-/-**	**-/-**	**L1/no**	**-/no**	**-/no**	**L1/no**	**-/-**
FC.EFCS(H)	**L1/-**	**L2/-**	**L1/no**	**-/no**	**-/no**	**L1/no**	**L1/-**

Results Category II Criteria

	Hess Nonlinear	OLOP	Time domain Neal-Smith
FC.EFCS(F)	**yes**	**yes**	**yes**
FC.EFCS(H)	**no**	**no**	**no**

LEGEND

L1,L2,L3	Predicted CHR
yes,no	Predicted PIO susceptibility
-	Criterion doesn't include prediction

Note: EFCS version F showed PIO tendencies
EFCS version H is the updated, PIO-free configuration

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Remedy to PIO

“Conventional” Methods

- Change Hardware
  - Actuators
  - Feel System Characteristics
  - Tail Size
  - etc.
- Change Control Laws
  - Control Allocation / Architecture
  - Control Sensitivity[*]
  - Reduce Phase Lags / Filtering[*]
  - System Bandwidth[*]
  - Loop Gains[*]
  - etc.

“Alternative” Methods

- PIO Suppression Filter
  - Attenuate Pilot Command At Predefined Pilot Operating Conditions
- Software Rate Limiters With Phase Compensation
  - Reduce Phase Loss Under Rate Saturation

[*] These methods were applied during the development of the example aircraft to fix the problems

On most cases of PIO experienced in the past, the problems were discovered in a relatively late phase of development, or even, during routine operation. A solution that allows the established control law structure to remain the same while eliminating PIO susceptibility surely is preferable.

Goal: Look for methods that solve the PIO problem without having to redesign control laws.

PIO Suppression Filter
Initial Design

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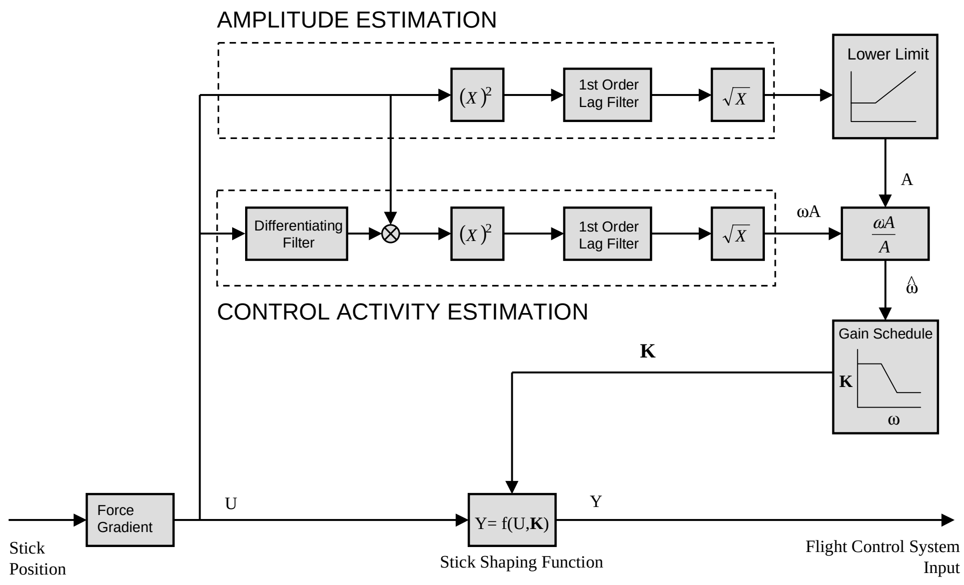


REF

Powers 1981

PIO Suppression Filter Functionality

Stick shaping function usually is a 3^{rd} order polynomial:

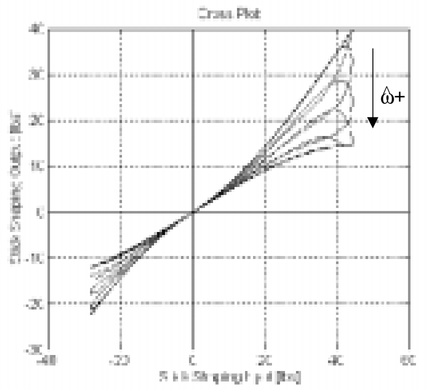
$Y = u\,(\,k_1 + k_2 \cdot |u| + k_3 \cdot u^2\,)$

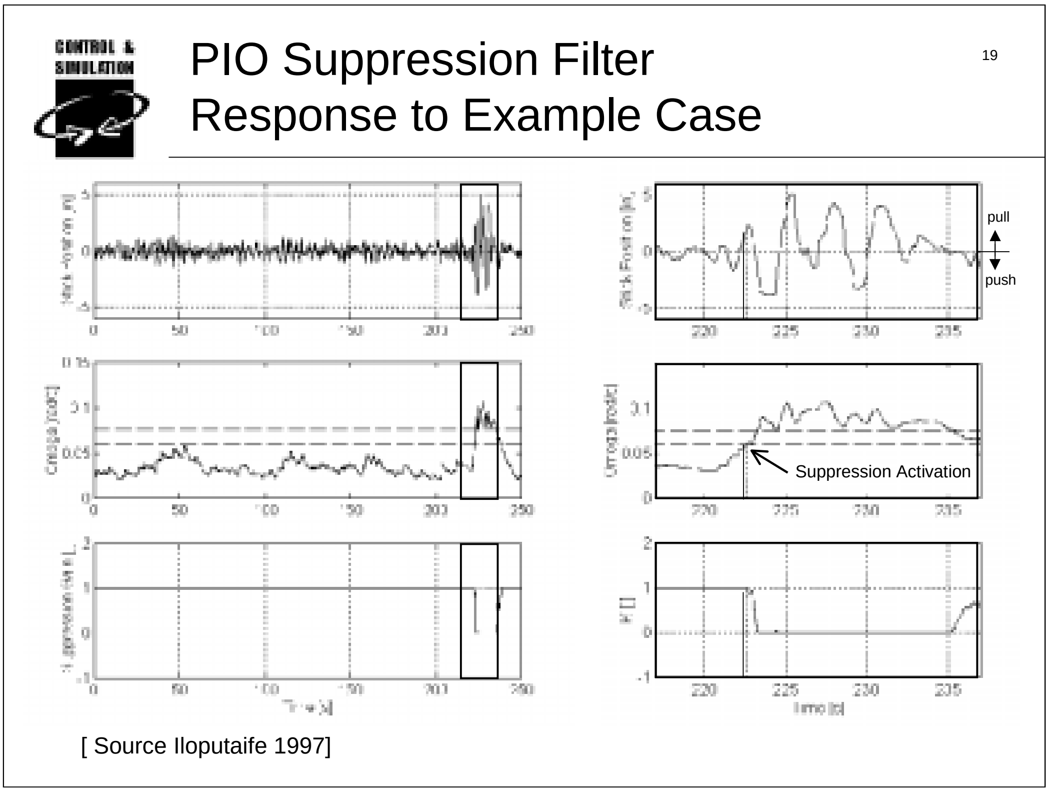
Suppression is obtained through:

$Y = u\,(\,k_1 + k_2 \cdot |u| \cdot \mathbf{K} + k_3 \cdot u^2\,)$

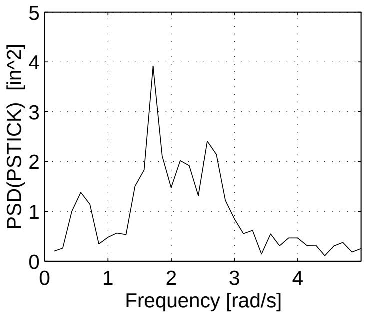
In which **K** is The suppression gain

<u>“Stick desensitizing”</u>

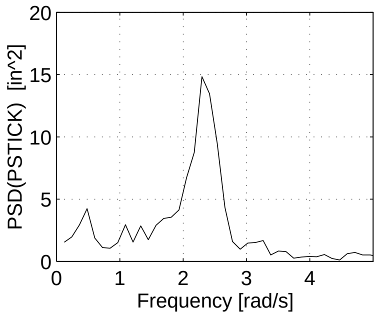




PSD of Stick Deflection Signal



Excluding PIO Frame



Including PIO Frame

Sampling Rate
f_s=10 Hz
No. of Samples
N=2,300
Frequency Resolution
$\Delta\omega$=0.14 rad/s

Conclusion:

During ‘normal’ task execution, pilot inputs contain energy in the frequency region of the actual PIO (which is about 2.3 rad/s)

REF

Iloputaife 1997

Phase Compensated Rate Limiting Schemes (Rundqwist - Saab Military Aircraft)

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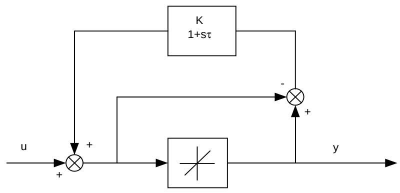
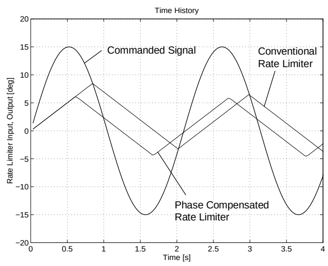
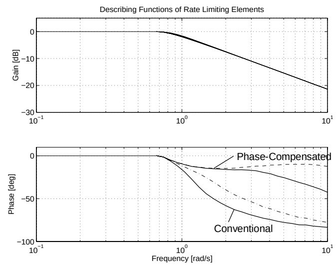
Concept:

- Under rate saturation, excess in demand is fed back
- Rate limiter command signal is attenuated
- Result: Output will change direction when input does







REF.

Hanke 1995

Rundqwist et al 1997

Phase Compensated Rate Limiting Schemes Effect on Closed-Loop System Using OLOP

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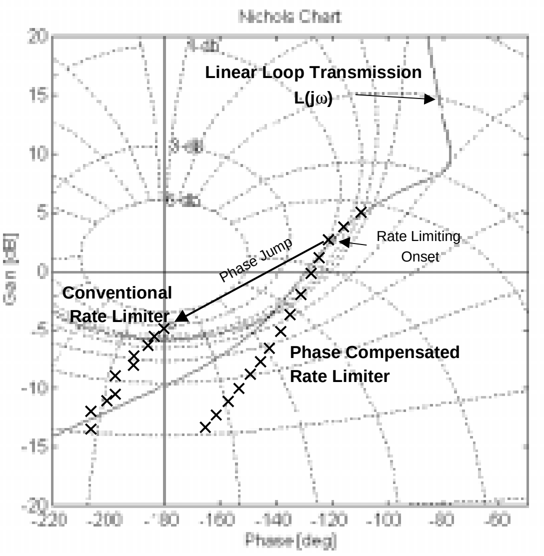
Stability Margin Analysis

Conventional rate limiting:
Phase Jump, undesirable

Alternative rate limiting
Avoids Phase Jump

Retain stability with same rate limit imposed on system



Conclusions

- Category II PIO criteria were successfully validated against a limited selection of example aircraft configurations
- When designed properly, a PIO suppression filter can identify a developing PIO And take avoidance action.
- Phase compensated rate limiters can alleviate the severe penalty associated with rate saturation in a closed-loop system.

Further Work

- Perform similar analysis for other PIO data
- Compare results of this study with recent experimental flight test data
- Address effect of structural dynamics on handling qualities and PIO
- Incorporate modern tools for stability analysis (mu, LMIs)
  Goal: towards category III PIO prediction

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Duda, H., Hovmark, G., Forssell, L.; 'Prediction of Category II Aircraft-Pilot Couplings – New Experimental Results'; AIAA-97-3499.

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[a]**Hess, R.A.**; 'A Unified Theory for Aircraft Handling Qualities and Adverse Aircraft-Pilot Coupling'; AIAA-97-0454.

[b]**Hess, R.A.**; 'Assessing Aircraft Susceptibility to Nonlinear Aircraft-Pilot Coupling/Pilot Induced Oscillations'; AIAA-97-3496.

[c]**Hess, R.A.**; 'A theory for the Roll-Ratchet Phenomenon in High Performance Aircraft'; AIAA-97-3498.

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Backup Slide
Results TDNS Criterion

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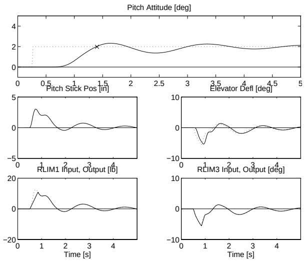
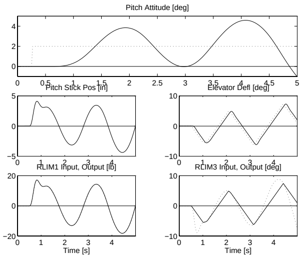


Time Domain Neal-Smith Response for Software Version H. Acquisition Time D=1.4 seconds.



Response for Software Version F; Same Conditions

Discrimination between good and bad configurations lies in Acquisition Time D for which system grows unstable.

Software Version H allows a smaller acquisition time

Criterion definition doesn't yet provide clear boundaries for D

REF

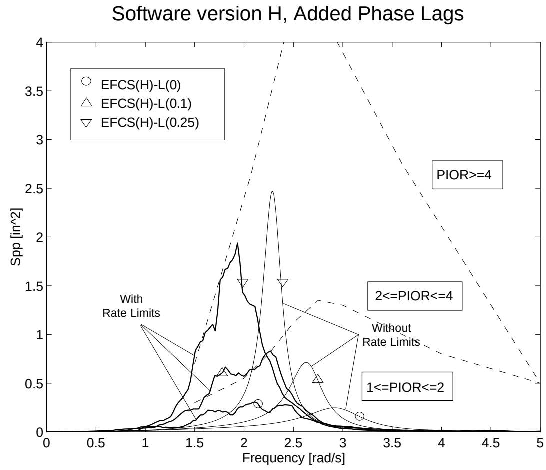
Bailey et al 1995, 1996

Backup Slide
Results Hess Nonlinear (i)

26

Resulting Hess mapping for
- Linear system
- Active rate limiters

(Note: Mapping for Software version F (old) is not plotted; it results in an unstable system, caused by excessive rate limiting)



REF

Hess 1989, 1997[a,b,c], 1998

Hess et al 1998

Backup Slide
Results Hess Nonlinear (ii)

27

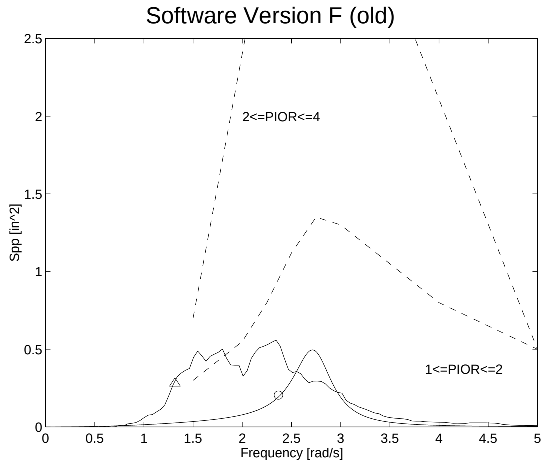
Phase Compensated Rate Limiting Schemes
Effect on Closed-Loop System Using Hess

Application of Hess method

Linear Hess mapping yielded solid PIO-free prediction

Inclusion of conventional rate limiter drove pilot-vehicle system unstable

System with phase compensated rate limiters is stable, but not predicted solid PIO-free (boundary has not been thoroughly validated)



Flight Testing for PIO

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Introduction

- Theory reduced to practice
- Developed intermittently over 32 years
- Highly nonlinear process
- Theory applied to numerous aircraft cases at EAFB since 1975
  - Several PIO predictions prior to flight test
  - Two non-PIO predictions
- Incorporated into TPS curriculum since 95B

Priorities

- Solve the airworthiness problem
  - Eliminate safety-of-flight issues related to PIO
    - PIO sensitivity training
    - Proficiency training
- Let the subsystems people deal with Cooper-Harper ratings and psycho-babble
  - Performance definitions are negotiated items
  - Workload is indefinable

A Question:

- No self-respecting engineer would design a servomechanism using criteria that are routinely accepted for piloted control of airplanes.
- Why should a FCS be designed to less stringent criteria than a floppy disk drive servo?

The Process

- Predict/Test/Verify
  - Characterize the Expectation
  - Exercise Experimental Technique
  - Understand the Results

Predict

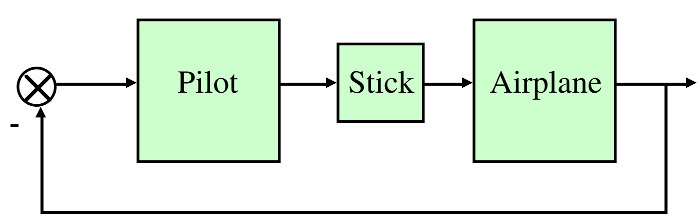
- Theory or Criteria
  - Smith-Geddes (implemented in the RSMITH software)
- Simulation
  - Simulate what?
    - HQDT

Aside: Definition

- PIO is pilot-in-the-loop oscillation
- PIO generally refers to pilot-in-the-loop instability

Aside: Characterizing PIO

- PIO due to excessive phase lag in the airplane
- PIO due to excessive command gain (stick sensitivity)



Aside: Phase-Gain Interaction

- The RSMITH software was written to account for the interactions
  - Predicts CHR for worst-case tracking
  - Predicts max stick sensitivity to avoid PIO

Aside: Stick Sensitivity

- The dominant HQ parameter
  - Overrides phase-based criteria (including Smith-Geddes)
- Typical airplane:
  - Stick sensitivity for no-PIO = insufficient authority to maneuver
  - PIO susceptible
  - Non-FBW transports are possible exceptions

Testing for PIO

- No Phase 3 (Cooper-Harper) testing
- HQDT -- the only maneuver that works
  - A sufficient criterion for PIO
  - Go/No Go engineering criterion
    - Closed loop task
    - Divergence = PIO susceptibility
    - Convergence = Not PIO susceptible
    - Task is not a factor
    - No Cooper-Harper ratings, no performance standard

Aside: HQDT

- Unnatural act
- The old guys hate it
- The new guys have trouble with it
- Has a theoretical basis: sufficient condition for PIO
- T-38 experience: proof that susceptibility does not equal unsuitability

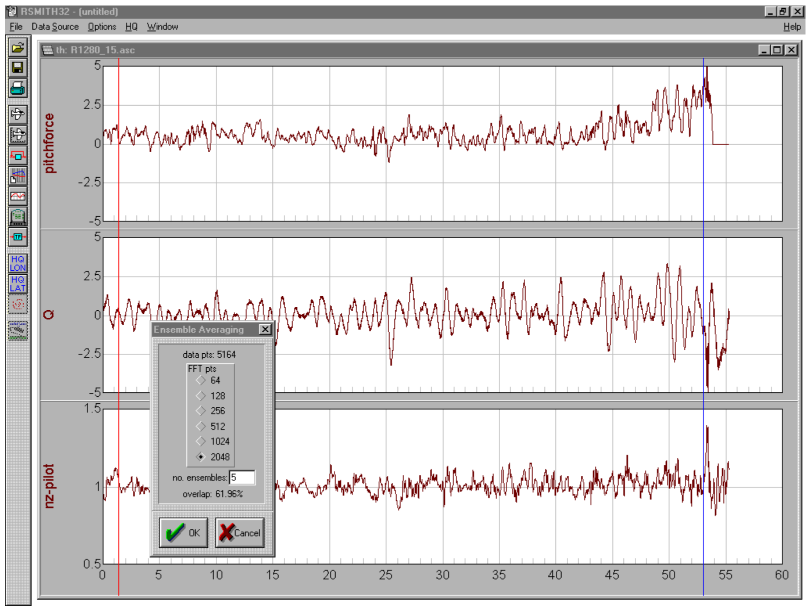
Understanding the Results

- Priority: Verify that you tested what you thought you tested
- Identification of aero parameters
- Model the FCS + airframe
- Freq response analysis of flight data to confirm model validity
- Write a tech report based on fact, not expectation

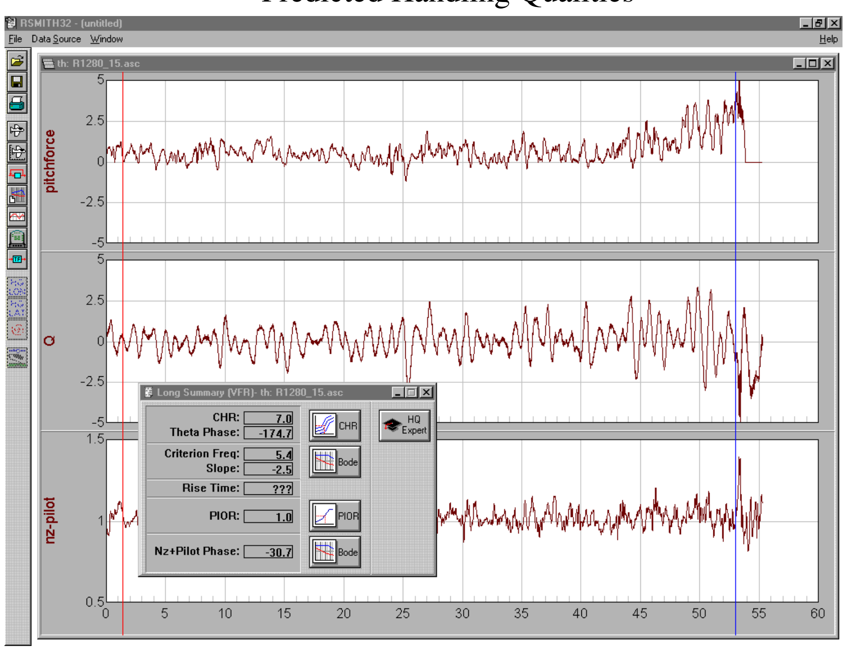
Case History

- Approach & landing task
- Control laws designed to satisfy Smith-Geddes criteria using RSMITH program
- Predicted Level 1
- Flight test: Level 2/3
- Initial reaction: failure of criteria
- Fact: Invalid aero model and VSA mech; criteria worked

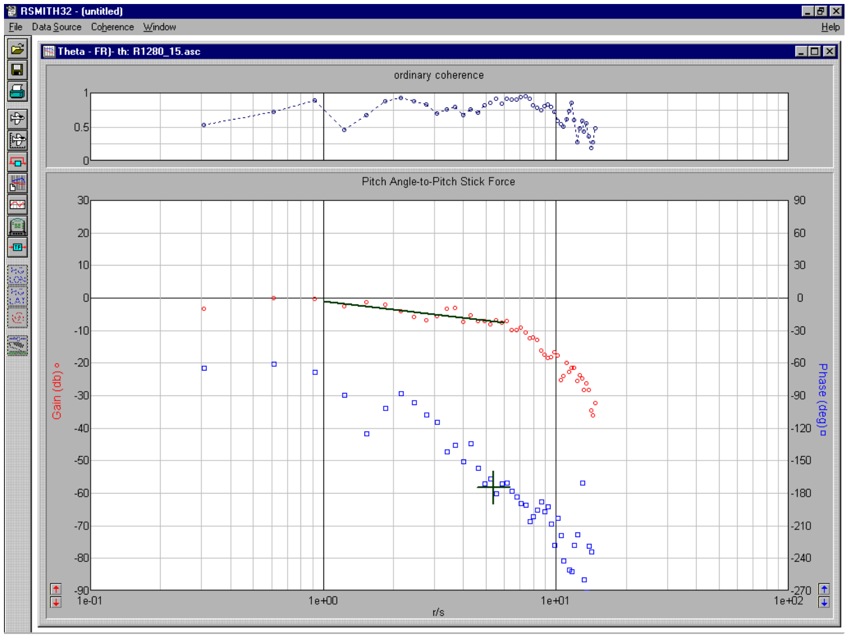
Approach & Landing: PIOR = 4 (R1280_14)



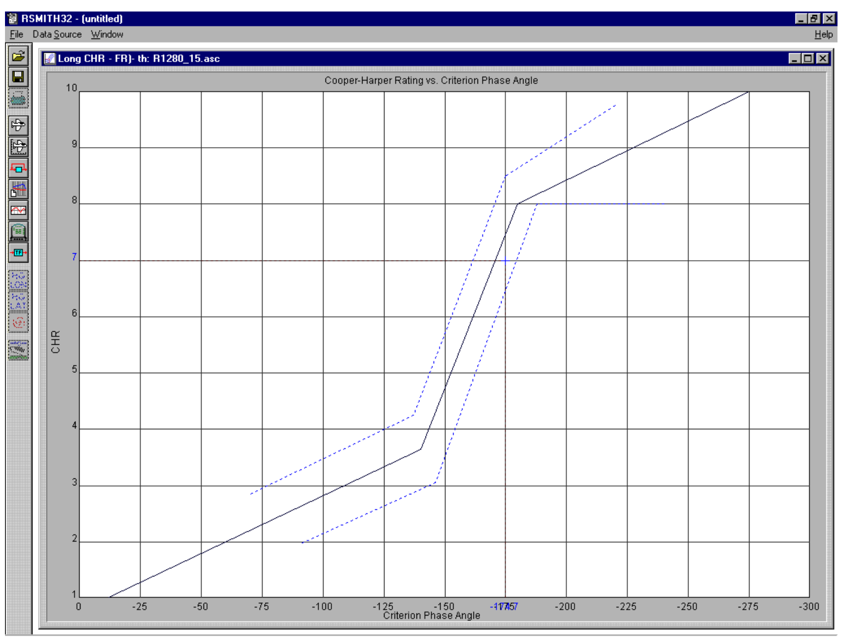
Predicted Handling Qualities



Slope Parameter & Criterion Phase Angle



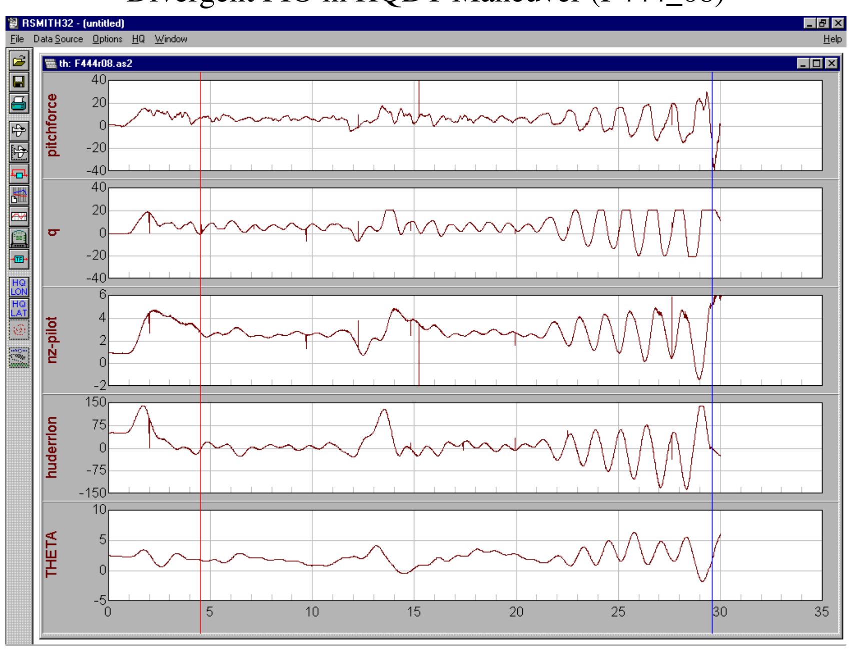
CHR vs Criterion Phase Angle



Case History: HQDT

- HUD tracking task, simulated air-to-air
- PIOR = 5
- Phase 3 tracking: CHR = 8/7/6/5/7
- Phase 3 tracking: PIOR = 5/5/3/3/3

Divergent PIO in HQDT Maneuver (F444_08)



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Use of In-Flight Simulators for PIO Susceptibility Testing and for Flight Test Training

By
Michael Parrag
Veridian Engineering (Calspan)
PIO Workshop
Dryden FRC, Edwards, CA
April 1999

The common denominator for both developmental testing and flight test training

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Realistic task in a realistic environment with uncompromised visual and motion cues

Before talking about the in-flight simulator "tool" in the PIO context let me say a few words about PIO phenomenon from a piloting viewpoint - having endured many as an evaluation pilot on research programs and having witnessed hundreds as a not so casual observer or safety pilot in a number of our in-flight simulators

I would like to briefly review several aspects of the PIO phenomenon:

- The variety of pilot input ⟶ aircraft response features that cause unpredictability, a root causal factor in PIO's
- The pilot's way to characterize a PIO in terms of how it affects this piloting task
- The circumstances that may trigger PIO events.
- Using the understanding of the above factors to structure flight test methodology oriented at uncovering PIO susceptibility
- Finally, this will lead to how the in-flight simulator is a safe and cost effective tool to accomplish flight test objectives

Response Unpredictability

<u>Primary causal factor for PIO</u>

Response Unpredictability

Predominantly a situation where initial response to pilot input miscues pilot as to where response will end up

or

pilot simply <u>does not get expected response</u> for a given input

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Potential Sources of Unpredictability

- Very initial response
  - time delay
  - onset rate → too high / too low
- Mismatch between time to first perceptible response and response buildup
- Steady state sensitivity

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Potential Sources of Unpredictability (Cont.)

- Poor correlation between pilot sensed responses

  e.g. pitch rotation vs 'g' buildup (in up and away flight)

  or

  pitch attitude and flight path angle (in P.A.)

- Dominant cue creating unintended loop closures (synchronous behavior)

  e.g. effects of n_{z_p} and n_{y_p}

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Potential Sources of Unpredictability (Cont.)

- Non linear effects
  - large and sharp (sudden) changes in characteristics such as in command gain scheduling

    or

    in response characteristics
  - Mechanical Non-Linearities
  - rate limiting in surface actuators or in software along command path
- Control misuse with exotic FCS modes

  or

  when <u>intuitive</u> pilot behavior can get you in trouble
- Excursion into non-linear aerodynamics
  - hi alt/hi Mach - pilot vehicle motions venture into Mach buffet or stall buffet

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Potential Sources of Unpredictability (Cont.)

- A major design culprit

⇩

- Overaugmentation

- excessive FCS gains in name of "robustness" or "agility"

Potential Sources of Unpredictability (Cont.)

- Some outcomes:
  - overly abrupt dynamics in pitch/roll

    causes staircase input/response in gross acquisition and causes hi freq/low amplitude PIO in fine tracking (bobbles)

  - requires use of more sensor filtering ⟶ time delay
  - drives rigid body dynamics closer to aeroelastic modes structuring filtering ⟶ time delay
  - hi fb + hi command gains ⟶ rate saturation more likely
  - often worse in turbulence
  - unnecessary wear/fatigue on actuators, surfaces and associated structures

Potential Sources of Unpredictability (Cont.)

- Another major design culprit ⟶ FCS complexity
  - designer cannot anticipate all possible interaction between FCS and pilot

    ∴ cannot guarantee "PIO free"

Types of PIO

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Pilot's Interpretation
based on how PIO
interacts with task

Types of PIO (Pilot's Interpretation)

- PIO's have two distinguishing features namely, frequency and amplitude, that determine how the pilot can deal with PIO in context of a task

Examples

- Hi freq, low amplitude such as in roll with very short τ_R

$\Downarrow$

roll ratcheting

  - excessive p causes significant n_{y_p} which cause rapid reversals by pilot - settles into "dominant cue/synchronous behavior"
  - viewed by pilot as very annoying but task remains controllable; pilot can easily judge average of PIO's

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Types of PIO (Pilot's Interpretation) (Cont.)

- Low freq., larger amplitude ⟶ often seen with rate limiting
  - pilot is unable to judge average of oscillations
  - generally not controllable if task constraints do not permit pilot to back out
- Medium frequency ⟶ gray area; degree of problem caused in task depends on:
  - amplitude of PIO
  - how much he is "driven" by a dominant cue
  - whether pilot can manipulate "average" to continue task
  - personal piloting technique - can pilot tone down his inputs?

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Circumstances which may "trigger" PIOs

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Circumstances which may "trigger" PIO's

- Found accidentally in an aggressive or high precision task scenario when undesireable aspects of the Pilot-Vehicle System and/or environment come in coincidence or change unexpectedly
  - major objective during development should be to minimize risk of this
- Uncovered during flight test by a determined and disciplined process of exploration and discovery
  - utilizing high gain tasks under demanding environmental conditions
  - process intended specifically to prevent "accidental" discovery of PIO where consequences are generally more serious
- In both cases, pilot demands rapid response and precise performance

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Circumstances which may "trigger" PIO's

- In the course of a high gain task scenario, when one or more undesirable elements influencing the Pilot-Vehicle System closed loop performance surface unexpectedly
  - In general, when sudden or anomalous changes occur in pilot behavior, effective vehicle dynamics or in feedback to the pilot
  - Atmospheric upsets such as:

    turbulence
    cross wind
    wake turbulence
    wind shear

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Circumstances which may "trigger" PIO's (Cont.)

- FCS mode change <u>during</u> a high gain task

  esp. with significant change in [A/C + FCS] dynamics, trim change or FCS dead time

- Mode change with gear/flaps or air/ground switch or unexpected FCS mode due to erroneous input from aircraft sensors

  e.g. FCS gains for wrong flap deflection

- Mixed manual and auto FCS modes when intuitive behavior mixes with auto control law to give unpredictable response

  e.g. auto compensation for engine out - - - creating control problem when pilot does get in loop

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Circumstances which may "trigger" PIO's (Cont.)

- In course of low gain monitoring tasks (pilot out of loop), sudden change:
  - Surprise (shock) - <u>startle</u> effect

    "hours of boredom punctuated by seconds of sheer panic"
    sudden entry into control loop due to upset or change in pilot's perception ⟶ often results in much bigger correction than needed

    e.g. akin to sudden awareness after dozing off at the wheel of a car

  - unexpected actuation of some a/c configuration device such as auto speed brakes, L.E. slats
  - system failure ⟶ e.g. runaway trim, sensor or display failure

Circumstances which may "trigger" PIO's (Cont.)

- Upset after "hidden onset" e.g. autopilot becomes saturated by turbulence upset, hinge moments due to ice - - - then "lets go";

  pilot is faced with out of trim upset

- above scenario but under conditions where handling qualities are marginal + close to aircraft limits
- lack of "situational awareness" leading to inappropriate interaction between pilot and automatic systems
- "pilot and copilot fighting each other" - - - on the controls

Circumstances which may "trigger" PIO's (Cont.)

In Summary

trigger event + unpredictable response

PIO is outcome of the latter only or both

The Determined "PIO Search" Flight Test Process

- Objective is to <u>minimize</u> risk of PIO occurrence in operational use
- Need to find the "black holes" in flight test - military testing - civil certification

To ensure coverage of vast set of circumstances in which PIO's can occur

Need to test <u>in combination</u>:

- All potential [aircraft + FCS] modes/configurations
  - low probability of occurrence is <u>not</u> excuse not to test
- Relatively extreme environment conditions - progressively but sufficiently early
- Aggressive yet high precision tasks
- Clever introduction of "trigger events" described previously - to reproduce surprise and stress to force "unusual control inputs"

This is difficult to implement!

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Elements of rigorous/determined PIO search process

- High gain tasks

  need to work high frequency portion of PVS to experience phase lags associated with many initial response problems

  $t = 0^+ \Rightarrow$ high freq

- Unfavorable atmospheric conditions
- Secondary task loading
- Piloting technique
- Urgency of control action
  - maybe combined with triggers?
- State of pilot's situational awareness

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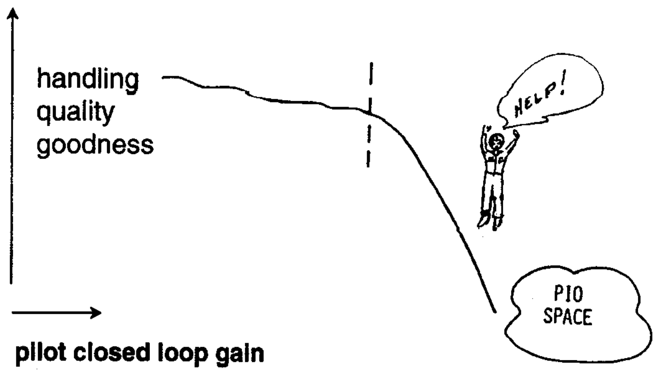
Must pay careful attention to these process elements because dealing with flying quality CLIFF



GOING OVER IS SENSITIVE TO PROCESS ELEMENTS

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TASK

- PA ⟶ Approach
  vs
  Flare and Touchdown
  Lake Bed vs Runway!
  vs Carrier

- UP AND AWAY ⟶ Formation
  vs
  A/A Tracking
  vs
  A/A Refueling

Need Tight (Demanding) Task for Proper Discrimination!

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Closed-Loop Standards of Performance

- Well Defined Predetermined Standards for

  Desired Performance
  Adequate Performance

  e.g. in terms of mil errors for tracking or touchdown box on runway

- Ensure that pilots are proficient in mechanics of task

Environmental Factors

- Turbulence including gust upsets
- Cross-winds
- Day-Night; - VFR - IFR
  i.e. Visual Cues
- Secondary Task Load

Pilot Closed-Loop Gain

- **Aggressiveness** in Task
  - Operationally Realistic
  - Pilot Chooses ! can back out!
- **"Pucker Factor"** - - - Forced On Pilot by Environment/task constraints
  - PIO's ARE NOT Optional

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Representative Piloting Technique

- Aircraft needs to be PIO safe for entire piloting population
- Piloting population is not uniform
  - There are low gain predictive types
  - There are high gain "ham fisted" types
- Both types need to be covered in PIO search, but especially latter
- Should also include:
  - Pilot unfamiliar with particular aircraft being tested, unbiased first opinions can be very telling
  - Test pilots who have experienced PIOs in past and who can effectively communicate their evaluations

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Urgency of Control Action

- Need to brief pilots:
  - to initiate aggressive gross acquisition
  - about compelling and immediacy to recovery from upset
  - "time to acquire" is the critical element

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State of Pilot's Situational Awareness

Situational Awareness (S.A.) ⟶ Pilot being fully cognizant of current aircraft state (configuration, FCS mode, autopilot mode etc.), of appropriate control strategy, or of his environment (weather, other aircraft)

Lack thereof or sudden change in S.A. may generate trigger or otherwise cause an "inappropriate" control input

- may be related to workload, understanding of FCS modes, piloting technique etc.
- consideration of the above possibilities needs to somehow be worked into the test plan

e.g. doing "blind" tests when safely feasible

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Tools of Pilot-in-the-loop Tests

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With Current New Technology - - FBW Aircraft

- Reliance on predictive analytic metrics

  Inadequate for handling qualities

- Pilot-in-the-loop evaluations essential

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Pilot-in-the-Loop Evaluations

- Only means of integrating all dynamic elements in closed loop

  Pilot

  Controllers/Feel System

  A/C + FCS

  Displays

  Weapon Systems

  In context of mission-oriented tasks

- Only credible means of assessing handling quality goodness and minimizing risks of hidden "cliffs"

Tools of Pilot-in-the-Loop Evaluations

- Ground-Based Simulators
- In-Flight Simulators
- Prototypes
- Operational Vehicles

Tools of Pilot-in-the-Loop Evaluations

Ground Based Simulators

- Considerations:
  - Readily available at design site
  - Serves key role in developmental evolution of dynamic elements
  - Limitations:

    Fidelity of synthetic visual and motion cues

    worst in conditions where many current FCS problems erupt

    Task environment ⟶ control strategy (can be quite different from flight)

    Lack of real flight stress

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Tools of Pilot-in-the-Loop Evaluations (Cont.)

- History indicates that for demanding high-gain tasks, ground based simulation has often been misleading - failed to expose dangerous problems

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Tools of Pilot-in-the-Loop Evaluations (Cont.)

- In-Flight Simulators (IFS)
  - Visual and motion cue environment correct/real, not synthetic
  - Real flight stress
  - Real piloting tasks

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Tools of Pilot-in-the Loop Evaluations (Cont.)

- In-Flight Simulator (Cont.)
  - Limitations
    - If IFS Not 6 DOF ⟶ some cues may not be fully representative
    - A number of scenarios outside capabilities of currently operational IFS's.

      e.g. in high α etc.
    - Only as good as model
  - However, for a given "model" ⟶ gives most credible handling quality answers
  - Generally much more credible effects of turbulence than in ground sim

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Objectives of IFS

- Verify/check ground sim results in real flight environment
- "Calibrate" ground simulator
  - Test pilots become tuned how to better use it for credible results given its particular cueing limitations.
- Historically has brought small dedicated problem-solving oriented flight test team together
  - Fostered communication

Pilots ⟷ Engineers ⟷ Managers

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Tools of Pilot-in-the-Loop Evaluations (Cont.)

Prototype Vehicle

- Very Costly Tool

  economically and from schedule viewpoint
- High risk environment in which to test potentially questionable or unknown characteristics
- High Cost and Risk Tool in which to test modifications/fixes

Operational Vehicle

- Once a vehicle is operational problem, fixing is a major fiasco

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Test Pilot Evaluation Tools

- Flight Test Tasks/Techniques
- Communication Tools

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Flight Test Tasks

"Real" Tasks

- Using no special displays
- Single element or combination of elements from an operational scenario
  - pitch or roll attitude captures
  - 45° bank level (const. altitude) turns with aggressive reversal
  - Close formation flight
  - Air to Air Tracking
  - Probe and Drogue refueling task
  - Offset landing approaches
  - aggressive alternate tracking of runway edge @ 100 ft AGL (or altitude safely appropriate for particular aircraft size)

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Flight Test Tasks (Cont.)

Synthetic Tasks

- Tracking task presented on a convenient pilot display such as:

  HUD (Head Up Display)
  MFD (Multi Function Display)
  Attitude Director Bars

- or presented on a removable LCD display with tasks preprogrammed on a P.C. computer (demonstrated in Learjet)

- Tasks must include single axis and combined axes elements with sufficient frequency and amplitude content on the tracking bar to test for PIO susceptibility with both single axis and coupled inputs
  - Need to brief pilot to aggressively work to keep errors zero
  - high gain ≡ aggressive closed loop behavior ⇒ works on high frequency portion of pilot - vehicle transfer characteristics
  - High freq ≡ quick or sharp initial response

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Flight Test Tasks (Cont.)

Synthetic Tasks (Cont.)

- this is region where problematic (cliffy) phase lags, phase rates and rate saturation effects occur
- Tasks should be programmed to occasionally require inputs from pilot that may seem operationally unrealistic

  e.g. rapid, full throw inputs

- Primary objective of tasks is to expose PIO/dangerous overcontrol potential
  - minimize risks of occurrence once aircraft is "certified"

- Hence, need to force test input sequences that stress the pilot-vehicle system to extremes even if unrealistic from an ops standpoint e.g. "klunk" inputs used by Saab
  - Flight test needs to establish margins around the operational envelope

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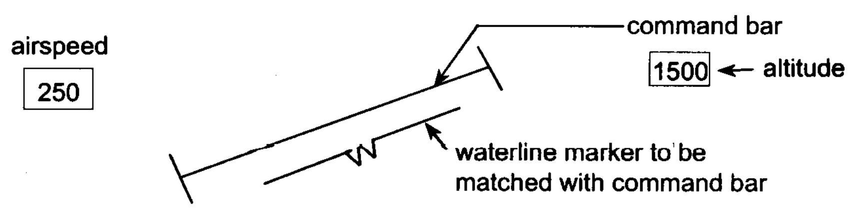
Flight Test Tasks (Cont.)

Synthetic Tasks (Cont.)

- Tracking bar programmable in both pitch and roll which the pilot chases with body axis fixed symbol such as a waterline pitch marker
  - This implementation has been successfully utilized on military aircraft by projecting this task on a HUD
  - demonstrated in Learjet projected on a head down LCD display
  - In either head up or head down implementation, can record tracking error in both pitch and roll and correlate with pilot input activity

Flight Test Tasks (Cont.)

Synthetic Tasks (Cont.)



Learjet LCD Display of Tracking Tasks

Flight Test Tasks (Cont.)

Synthetic Tasks (Cont.)

- Two types of tasks

  1. Discrete Tracking Task (DTT)
     - combination of steps, ramps in both pitch and roll but "coordinated"
     - can separately control amplitude of pitch and roll separately to match task to nature of aircraft being tested
     - objective is to elicit both gross acquisition and fine tracking activity

  2. Sum of Sines
     - combination of sine waves of different frequencies
     - 1st or 2nd order frequency roll off (filter)
     - pitch and roll amplitudes separately controllable again to match task to aircraft being tested
     - objective is to elicit aggressive fine tracking activity

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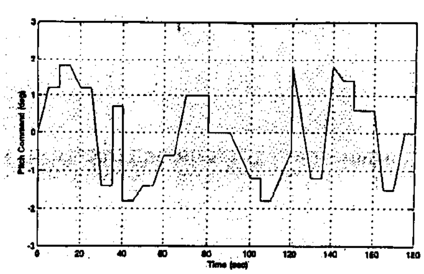
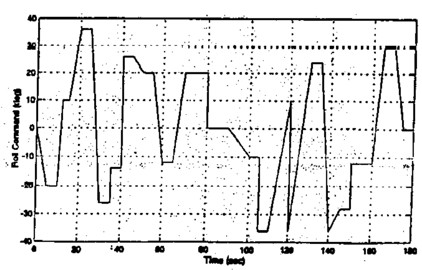
Flight Test Tasks (Cont.)





Discrete Tracking Task

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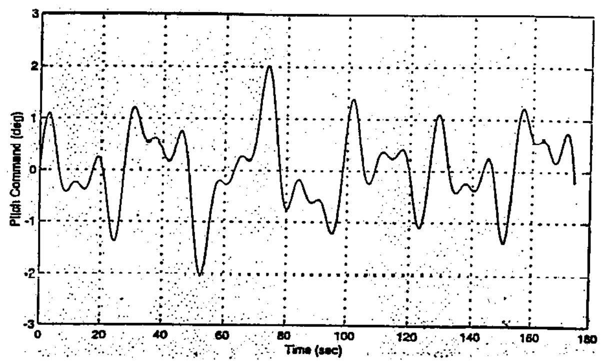
Flight Test Tasks (Cont.)



Sum of Sines Tracking Task
(similar in roll)

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Flight Test Tasks (Cont.)

Other Considerations

- "Triggers" of PIO should be inherent in developed tasks whenever feasible
- Need to consider task environment issues
  - effects of turbulence
  - conditions of visual cues
- FTT's must be tested against known problem configurations and <u>consistently</u> expose potential or latent "black holes"
- FTT's must generally indicate "good" aircraft to indeed be good

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Special Issues Pertaining to Civil Certification

- A major hurdle is to get past barrier from pilots or managers on test techniques that "transports are not flown this way" or that certain pilot inputs are unrealistic.
  - there needs to be recognition that flight test/certification test should establish adequate "margins"
  - ensure no "cliffs" on the edge of envelope
  - account for unusual inputs from "startle" factor

Test Pilot Communication Tools

- Need proper tools to ensure orderly process for test pilots to solidify and effectively communication their evaluation or assessment to engineers, managers, and other pilots
- Comment Cards
  - checklist for comments
  - comments are meat of evaluation data
- Cooper-Harper Rating Scale
  - consideration of "average pilot"
  - cutoff for "exceptional attention, skill or strength" in civil certification?

Test Pilot Communication Tools (Cont.)

- PIO Rating Scale
  - current scale
  - suggested modification
  - too much arguing about PIO rating scale when most important pilot evaluation issue is task/FTT's that expose problems - rest is merely organizing how pilot reports what he has seen

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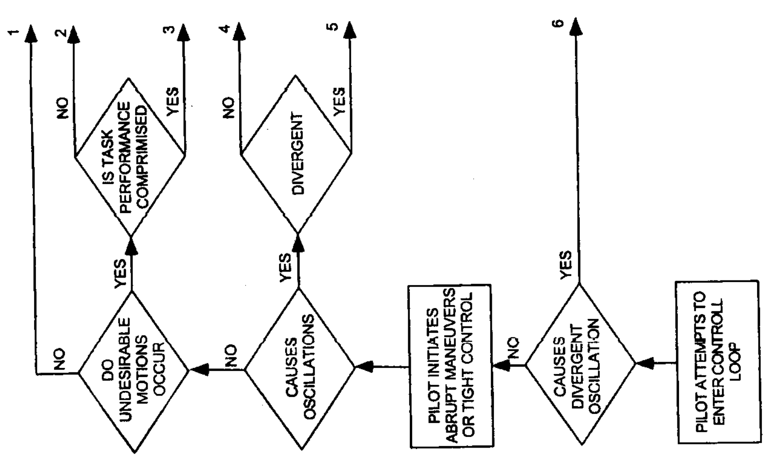
PIO Tendency Classification Scale
Current Scale



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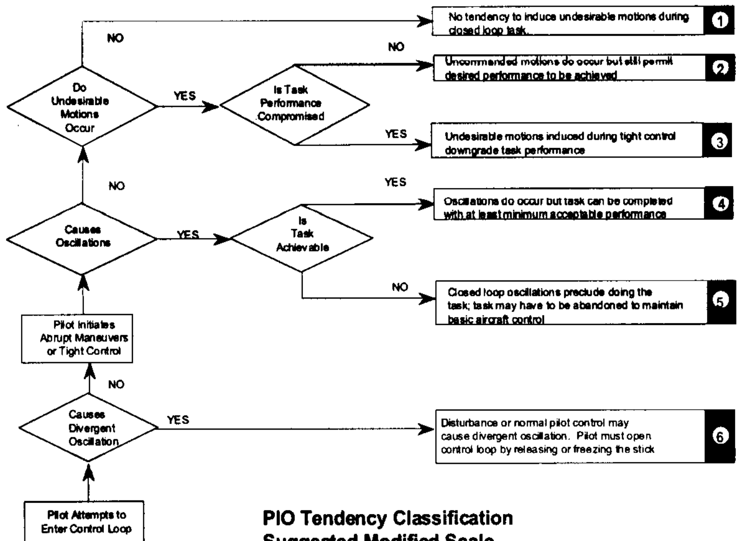

PIO Tendency Classification
Suggested Modified Scale

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Unique Instrumentation Requirements for PIO Related Flight Tests

- During Flight Test
  - Data sampling rates 30 hz or higher for rigid body PVS dynamics

    i.e. fast variables
  - Lower data rates for slow variables such as altitude airspeed
  - should get derivative of aircraft rotational rates and perhaps even 2nd derivative - - - "jerk" motions
  - instrument for n_{z_p}, n_{y_p}
  - should instrument for actuator rates and control margins

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Unique Instrumentation Requirements for PIO

- In Operational Use
  - Flight Data Recorder
  - Sufficient data channels to record critical variable
  - Sampling rates for critical parameters need to be at least 15-20 hz

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Management Issues Pertaining to PIO Problem

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Management Issues

- Industry awareness of PIO is poor
- Lack of understanding of phenomenon and implications to

  design process
  flight test process

- Flight test teams need specialized training to improve ability to test FBW in general and for PIO in particular
  - exposure of test pilots and FTE's to a variety of PIO's in in-flight simulator aircraft is excellent conditioner for test teams

  "A good scare is worth more than good advise"

  - makes them "true believers" in PIO search process

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Management Issues (Cont.)

- Managers need to support a structured approach to test process from early in design to service entry
  - use all the tools at their disposal, integrated recognizing each tool strengths and limitations
- Managers need to treat flight test as a process of discovery rather than as mundane validation of predictions
- What information from flight test needs to be communicated to the operational pilot
  - overcome the "marketing hurdle"

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Flight Test Training

- Exposure of test pilots and flight test engineers to real PIO's in the variety of tasks presented earlier becomes an invaluable career experience to:
  - Appreciate the significance of the phenomenon
  - Appreciate the criticality of various tasks and of task environment towards the propensity to PIO
  - Ensure that these flight test crews will appropriately adjudicate any test planning process with regards to PIO in which they will participate in the course of their career

Flight Test Training (Cont.)

to reiterate

"A good scare is worth more than good advice"

A Method for the Flight Test Evaluation of PIO Susceptibility

Thomas R. Twisdale & Michael K. Nelson
412thTW/TSFT/USAF Test Pilot School

Handling qualities testing is the most important of all flying qualities testing

Handling qualities are the dynamics, or characteristics, of the pilot plus the airplane.

Handling qualities testing is based on three principles

- **model validation test method**
- **build-up approach**
- **completeness**

Model validation test method

1. Predict the airplane response, based on a model.
2. Test the prediction.
3. Validate or correct the model, based on the test results.

Build-up approach

Testing progresses from the lowest to the highest level of risk.

Completeness

Evaluate the *FULL* spectrum of handling qualities.

Three phases of handling qualities testing

Phase 1: Low bandwidth testing

Phase 2: High bandwidth testing

Phase 3: Operational testing

Phase 1: Low bandwidth testing

Purpose:

- evaluate low bandwidth hq (smooth, low frequency, non-aggressive control)
- familiarization
- warm-up
- "get acquainted"

Test Maneuvers

- open-loop (*NOT* handling qualities)
- semi-closed-loop
- low bandwidth maneuvering
- low bandwidth tracking

Test data

- pilot comments
- time histories

Phase 2: High bandwidth testing

Purpose

- evaluate high bandwidth hq (abrupt, high frequency, aggressive, small and large amplitude control)
- "stress testing"
- "safety gate"

Test maneuvers

- HQDT (principally)
- simulated carrier approaches

Test data: pilot comments and ratings (PIO and analog scale)

Phase 3: Operational evaluation

Purpose: evaluate whether handling qualities are adequate to perform the design mission

Test maneuvers: depends on airplane and mission

Task performance standards: traceable to mission

Test data

- pilot comments and ratings (Cooper-Harper, PIO, analog scale)
- measured task performance

Phase 2: High bandwidth testing

Purpose

- evaluate high bandwidth hq (abrupt, high frequency, aggressive, small and large amplitude control)
- "stress testing"
- "safety gate"

Test maneuvers

- HQDT (principally)
- simulated carrier approaches

Test data: pilot comments and ratings (PIO and analog scale)

HQDT

special piloting technique:

track a precision aim point as aggressively and as assiduously as possible, always striving to correct even the smallest of tracking errors

Objections to HQDT

- pilots don't fly that way
- OK for fighters, but not for large airplanes
- causes degraded task performance
- HQDT makes any airplane look bad
- done for engineers, not pilots

Session V

ON-BOARD PIO DETECTION/PREVENTION

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BACKGROUND

- **THE BEST WAY TO AVOID PIO PROBLEMS IS TO DESIGN THE FLIGHT CONTROL SYSTEM SO THAT THE AIRCRAFT DOES NOT HAVE ANY PIO TENDENCIES**
- But…
  - Aerodyamic prediction methods (CFD, wind tunnel) are not perfect
  - Design criteria and analysis methods are not perfect, particularly with regard to the effects of significant nonlinearites
  - Flight control changes to fix PIO problems detected late in the development cycle can be "expensive" to fix

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THEORETICAL BENEFITS

- Quick, cheap fix
- Valuable safety net in flight test, even if not intended for operational use
- Detection algorithms can provide valuable data during development and flight test

3

KNOWN DRAWBACKS

- May only mitigate PIO tendency, not solve it
- Always impacts general handling qualities

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VARIOUS APPROACHES

- Suppression filters
- Rate limiting algorithms
- PIO detectors
- PIO preventers
  - Passive
  - Active
- Force cueing

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SUPPRESSION FILTERS

- Low-pass filter in the forward path to prevent pilot inputs from exciting PIO tendency
- Attenuates command and adds phase lag to the aircraft response, degrading general handling qualities, especially for high bandwidth tasks

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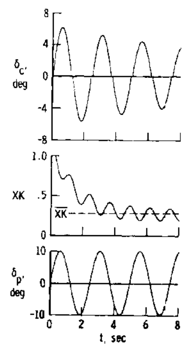
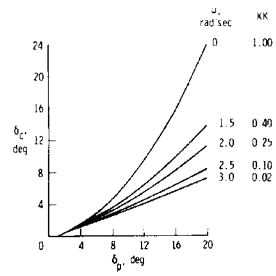
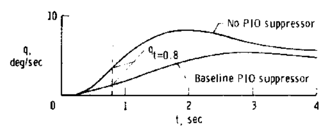
SPACE SHUTTLE ADAPTIVE PIO SUPPRESSOR



Output from sine wave input, A = 10 deg, ω = 2.5 rad/sec



Frequency-dependent attenuation



Pitch rate response to 15-deg δ_p step input

RATE LIMITING ALGORITHMS

- Eliminates or reduces the phase lag due to rate limiting
- Introduces a bias between commanded output and actual output, attenuates command and reduces control power
- Removing bias causes "uncommanded motions"
- Only good for PIO tendencies caused by rate limiting

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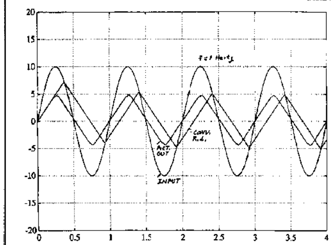
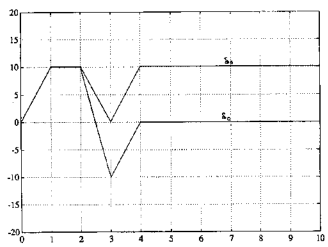
RATE LIMITING ALGORITHM

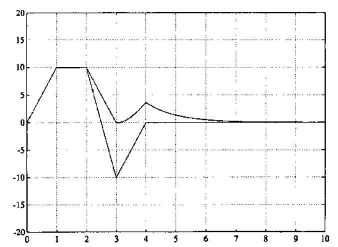


Basic Concept

"Uncommanded" Response Generated by Bias Removal



Bias generated by asymmetric input



RATE LIMITING EXPERIMENT ON LEARJET (Mar 93)

Pilot	Task	RLC	CHR	PIOR	Comments
A	BAT	Off	8	4	nonlinear, lumpy, seems like a delay but not time delay
		On	5	3	undesireable motions
	PA	Off	10	5	abrupt maneuvers get divergent behavior, large but slow amplitude divergence, no evidence during approach
		On	4	2-3	some lack of precision, 5 deg overshoots, sense that I'm in control, no tendency to get into divergence, precision not quite what I'd like, small wallowing, tendency to overcontrol, task compromised slightly
B	PA	Off	10	5	PIO prone, abrupt inputs do cause oscillations which may be divergent
		On	4, 5	2,2	no difficulties with PIO, small tendency to be imprecise, little more tendency to wallow when you try to be precise, trying to be more precise brought out tendency to overcontrol
C	PA	Off	10	6	no way to stay in the loop on that, holy s---t!, PIO max on the scale, stick all the way over and aircraft still going the other way
		On	-	-	still goes slow, could definitely feel rate limiting but it was not PIO prone like the last one, big difference

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PASSIVE PIO PREVENTION

- Warning activated by detection of PIO, rate limiting, or other related phenomena
- Warning can be:
  - Light
  - Audio warning
  - Warning on HUD
  - Force feedback through stick
- Pilot must recognize and adapt

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ACTIVE PIO SUPPRESSION

- Changes to control system activated by detection of PIO, rate limiting, or other related phenomena
  - Reduce forward path gain
  - Pass pilot input through low-pass filter
  - Force feedback through control stick
- May have more adverse effects than the PIO

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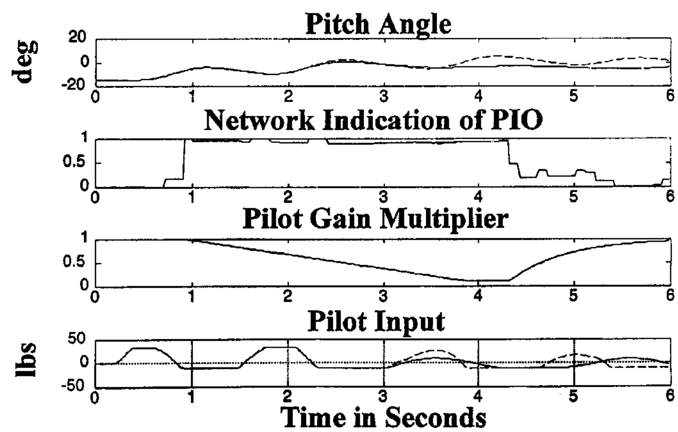
PIO DETECTION AND ACTIVE SUPPRESSION



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CONCLUSIONS

- These techniques can work
- Although not the first choice, they may present a program with an alternative to "complete redesign" or "tell pilot not to do that"
- Detection algorithms provide handy data analysis capability
- There are serious drawbacks, design of these algorithms should not be taken lightly

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Real Time PIO Detection and Compensation

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Thanks

- Charles Suchomel - AFRL, COTR
- Brian Stadler - AFRL
- David Legget- AFRL
- Thomas Cord - AFRL
- Ba Nguyen - AFRL

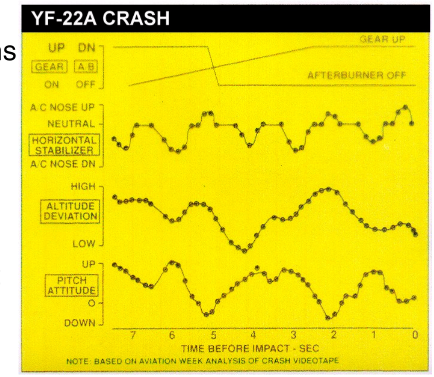
Accurate Automation Corporation

Neural Network Compensation Strategy for Preventing Pilot-Induced Oscillations

Air Force Phase II SBIR F33615-96-C-3608
COTR: Chuck Suchomel AFRL/VACD

Objective: Develop a Smart Neural Network-Based Controller to Prevent Pilot-Induced Oscillations

1. Recognize Pilot-Induced Oscillations In Data From Events Where PIO Have Played a Major Part
2. Designed a Neural Network To Recognize the PIO and Help The Pilot to Fly Out of the Problem
3. Designed an Advanced Hardware Controller to Validate the Concept
4. Patent Pending



Results to Date

Patent will be issued soon

Detector/Compensator tested in closed loop with simulated configurations on AFRL 6-DOF piloted simulator

Detector tested with F-16 PIO data, HARV PIO data, and simulated NT-33 data (MS-1)

Detector/Compensator tested in open and closed loop with simulated F-16

Results to Date

Designed hardware

- VME
- DSP
- NNP® interface
- VME to 1553 interface
- A/D, D/A, digital interfaces

Presentation Topics

- PIO Detection and Compensation
- Simulation Testing
- PIO Hardware

Concept

- While a PIO occurs, a detector flags the PIO.
- If no PIO is occurring, the detector outputs a zero.
- When the detector flags a PIO, a compensator is engaged.

PIO Detector Goals

- Real time operation
- Accurate
- Robust
  - configurations
  - pilots
  - noise
- Simple

PIO Compensator Goals

- Activated when PIO occur
- Never active when PIO not occurring
- Stops PIO
- Acceptable to Pilots

PIO Detection

- PIO detection is simple and clean
  - simple algorithm
  - runs in real time
  - only straightforward preprocessing is required
  - works in longitudinal and lateral axes
  - works for many configurations
  - accurate

PIO Compensation

- How to compensate for PIO is still unresolved.
  - We have tested simple authority reduction and a PIO filter
  - Pilot's do not like to have their authority reduced
  - Sometimes different situations call for different types of compensation
  - More testing is necessary.

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Algorithm Development

- We used MS-1 simulation data, HARV data, and F-16 simulation data to develop the detector.
- An iterative process was used to train the detector.
- The compensator was developed with simulated HAVE PIO configurations.

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Simulation Testing

- Tested detector with MS-1 PIO data
- Tested detector/compensator with simulated HAVE PIO configurations and simple pilot model
- Tested detector, advisory, and compensator in LAMARS simulator

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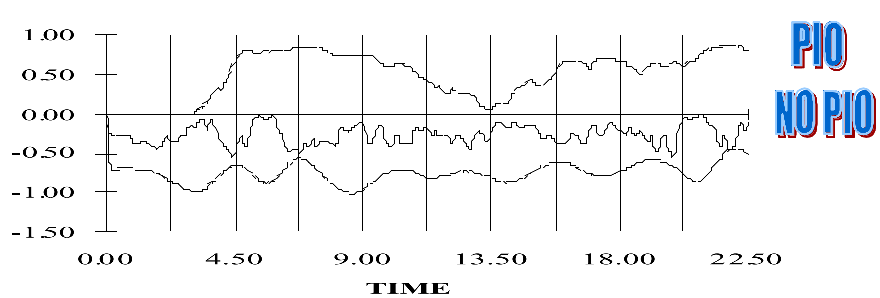
Detection of MS-1 Simulated PIO



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Piloted Simulation Testing

- Performed in AFRL LAMARS high-fidelity motion base simulator
- Tested a PIO detector and two compensators
- Gathered data to improve detection and compensation methods

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Piloted Simulation Testing Rational

- Only human in the loop testing can tell you how a compensator or advisory will effect the performance of a pilot.
- Pilot models are not adequate.
  - They are good only for initial testing.
  - Not all problems can be uncovered with pilot models.

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Major Questions

- Does the detector perform adequately?
  - Must not trigger when it shouldn't
- Does the compensator perform adequately?
  - Must not cause a bigger problem when it is on.
  - Preferably must allow the pilot to perform his task.

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Detection Issues

- Does the detector perform adequately?
  - Does is stay off when there is no PIO?
  - Does it come on when there is a PIO?
  - Does it work across a wide range of configurations?
  - Does it work across a wide range of pilots?
  - Is it robust to noise?

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Compensation Issues

- Does the compensator perform adequately?
  - Does it stop PIO?
  - Can the task still be performed?
  - Do pilots mind having their authority reduced?
  - Does filter induced delay cause other problems?

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Compensation Issues

- Do different PIO call for different compensation?
  - Use gain compensation with explosive PIO?
  - Use filter compensation with mild to medium PIO?
  - Use other methods?

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Compensator Types

- Gain Compensator
  - Ramp in
  - Ramp out
  - Minimum authority
- Filter Compensator
  - Ramp in
  - Ramp out
  - Minimum authority

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Simulation Testing Methodology

- Succinct matrix
  - HAVE PIO and landing task
  - HAVE LIMTS like configurations with tracking task
- Short look instead of long look
- Random presentation
- Repeats allowed
  - this allowed us to use short look without confidence levels

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Simulation Testing Matrix Advisory/Compensation Options

- Four Cases
  - PIO detection but no advisory, no compensation
  - Detection and advisory, no compensation
  - Detection and no advisory, compensation
  - Detection and advisory, compensation

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Simulation Testing Methodology - Pilots

- one Navy test pilot, one civilian acrobatic pilot, and five Air Force test pilots
- prebriefed pilots
- did not lead the pilots
- tried not to let pilots compare configurations
- performance feedback provided at end of run

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Simulation Testing Methodology - Pilots

- made pilots go through the scales when giving ratings
- rating/Questionnaire cards with pilot in cockpit
- debriefed the pilots
- frequent breaks

Simulation Testing - Pilot Subjective Data

- Pilot briefings
  - configurations, tasks, motion, ratings, adequate anddesired
- Pilot comment card
  - PIO scale (Mike Parrag - Veridian) and Cooper-Harper scale
  - Questions
- Pilot's asked to give frank assessment of algorithms

Simulation Testing - Configurations

- HAVE PIO - Category I
  - Baseline Longitudinal 2-1,3-1,5-1
  - Primary Longitudinal 2-5, 5-9, 5-10
  - Secondary Longitudinal 2-8, 3-12, 3-13
- HAVE LIMITS - Category II
  - 2P, 2DU, 2D, 2DV
  - Rate limit adapted to pilot to force PIO

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Simulation Testing - Pilots' Tasks

- Offset landing
  - pilot must land aircraft within target zone starting from an offset approach
  - HAVE PIO configurations
- Discrete tracking
  - pilot tracks steps and ramps
  - HAVE LIMITS

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Simulation Testing - Time Series Data

- All detector and compensator inputs, internal variables, and outputs
- aircraft state variables
- pilot outputs
- task and performance data
- pilot PIO indicators (trigger pulls at about where a PIO occurs)

Simulation Testing Results

- Detector works very well in pitch and roll

- Gain compensator stops PIO but pilots don't like it

- Filter compensator had problems

- Much analysis still to be done

Report number 20 is missing slides 31 to 34; they were unavailable at the time of publication.

Simulation Testing Result - Divergent PIO

Simulation Testing Result - NO PIO

Simulation Testing Result - NO PIO

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Simulation Testing Result - NO PIO

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Simulation Testing Results - Pilot Comments

- Advisory well correlated to pilot assessment of PIO
- Some pilots found advisory helpful
- Some pilots said advisory didn't give them additional information
- Some pilots commented on timeliness of detection

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Simulation Testing Results - Pilot Comments

- Pilots said gain compensation stopped PIO, but interfered with task
- Delay induced by filter compensator caused problems
- Pilots felt that motion helped them with tasks, especially landing

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Simulation Testing Results - Observations

- Pilots improved their performance over time
- One “golden arm” pilot could fly almost anything
- Pilots sometime adapted to gain reduction

PIO Compensation Hardware

- board hosts PIO detection and compensation algorithms
- DSP
- includes interface to multiple AAC NNPs.
- VME bus with 1553 interface
- A/D, D/A, and digital interfaces

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Conclusions

- Developed a *real-time* PIO detector
- Developed a *real-time* PIO compensator
- Tested detector and compensator in a high fidelity piloted simulators
- Continuing simulation testing
- Developing hardware

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Next Steps

- Analyze data
- More simulation testing
  - larger matrix, operational pilots, new advisories, force fœdback
- Flight Testing
- Develop PIO Classifier
- Develop a good compensation method

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PIO Detection with a Real-time Oscillation Verifier (ROVER)

David G. Mitchell
Technical Director
Hoh Aeronautics, Inc.

Pilot Induced Oscillation Research Workshop
NASA Dryden Flight Research Center
8 April 1999

Prevention of PIOs in Flight

- Fundamental goal is to prevent PIOs by design
  - On-board detector could be a valuable flight test tool
  - Application for failures, unusual loadings and flight conditions
- Monitor airplane responses and pilot inputs to look for:
  - Oscillations of proper frequency range
  - Airplane out of phase with pilot
  - Amplitudes of input and output large
- Concept developed under current contract
  - Has not actually been applied real-time
  - Applying for patent
  - Looking for follow-on funding for further development

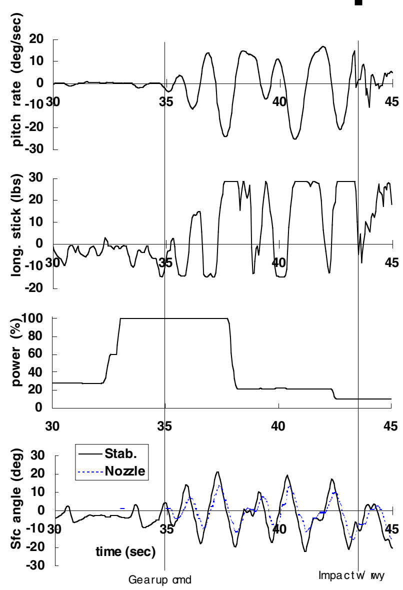
Real-Time Detection of PIOs

- **Time histories of dozens of PIOs have been examined in detail**
- **Underlying conclusions:**
  - **There is no clearly identifiable "pre-PIO" condition**
  - **Many of the precursors to PIO occur in normal operation**
  - **It will not be possible to detect and stop a PIO before it starts**
  - **The best we will be able to do is detect one in the first half-cycle (or so)**

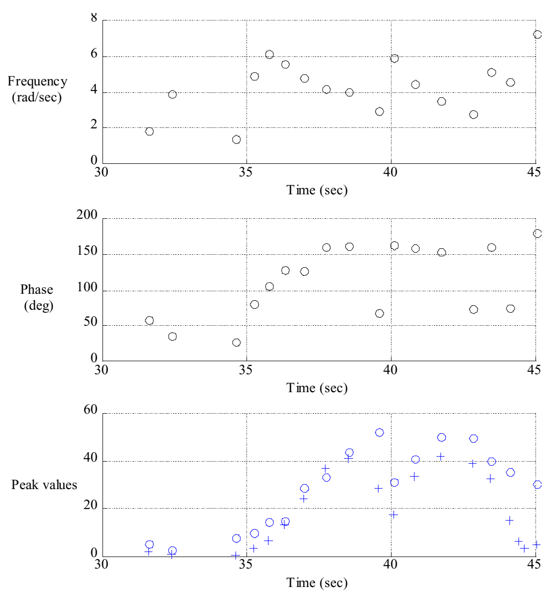
Real-time Oscillation VERifier (ROVER)

- Assumptions:
  - Pilot operates more or less sinusoidally
  - Pilot adopts synchronous behavior in PIO
  - Airplane is 180° out of phase with pilot in a PIO
- Apply a moderate amount of filtering
  - Bandpass to emphasize range of expected PIO frequencies
  - Both input and output filtered to minimize impact
- Test for:
  - Oscillation frequency within range for PIO
  - 90° phase lag between control input and pitch rate
  - Proper amplitude of input and output

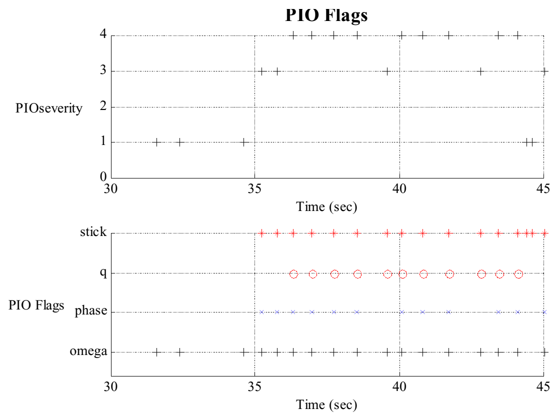
YF-22A Mishap



Output for YF-22A Mishap

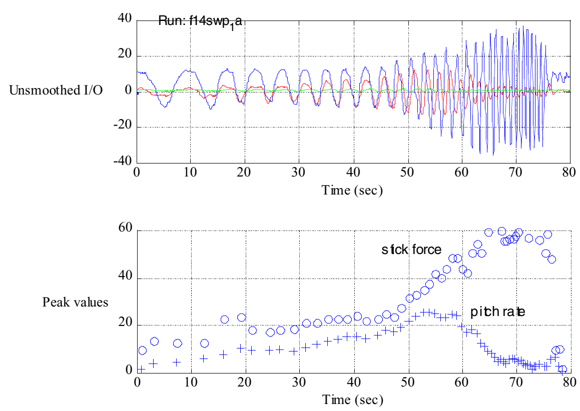


Output for YF-22A Mishap



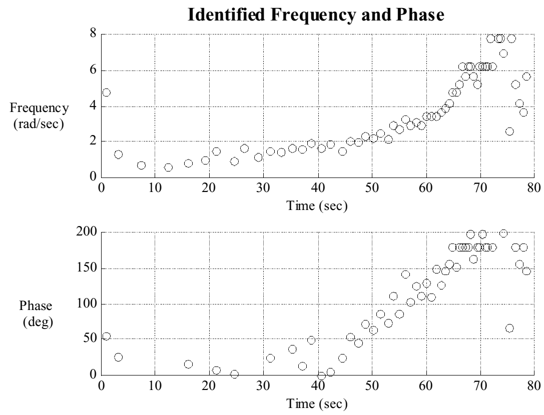
Application as a Flight Test Tool:

Time-domain verifier for frequency sweeps



Application as a Flight Test Tool:

Time-domain verifier for frequency sweeps



Continuing Development

- Extend to roll
- Extend to normal acceleration
- Select best filters for bandpass, removing noisy data
- Requires tailoring
  - Different flight conditions (higher thresholds up-and-away)
  - Different cockpit effectors (force *vs.* displacement)
  - Adapt to failures (reduce thresholds if sensors lost)
- Active interventions *vs.* alerting
  - Should depend upon complexity of flight control system, degree of instability, mission roles
  - Form of active intervention will depend upon flight condition

Pilot Opinion Ratings and PIO

Thomas R. Twisdale & Michael K. Nelson
412thTW/TSFT/USAF Test Pilot School

See Paper no. 4 in Appendix 3

THE NEED FOR PIO DEMONSTRATION MANEUVERS

Vineet Sahasrabudhe
David H. Klyde
Systems Technology, Inc.

David G. Mitchell
Hoh Aeronautics, Inc.

Pilot-Induced Oscillation Research:
The Status at the End of the Century
NASA Dryden Flight Research Center
6-8 April 1999

OVERVIEW

- Identify relevance of demonstration maneuvers for PIO
- Review USAF Handling Qualities Demonstration Maneuvers program
- Exposing PIO
  - Probe-and-drogue refueling example
  - HUD tracking example
- The need for PIO specific maneuvers
- Additional candidate PIO demonstration maneuvers

RELEVANCE TO PIO

- Objective of the USAF program was to develop a catalog of repeatable maneuvers to evaluate closed-loop handling qualities
- Some of the maneuvers included in the final catalog also exposed PIO and/or PIO tendencies
- The continued occurrence of PIO in operational aircraft (military and commercial) indicates a strong need to develop a similar catalog for PIO

DEMONSTRATION MANEUVERS PROGRAM BACKGROUND

- Phase II SBIR for the USAF Flight Dynamics Directorate
  - Air Force Technical Contact: Thomas J. Cord
- Phase I results published as STI TR-1298-1 and as Appendix C of WL-TR-94-3162
- Proposed Maneuver Catalog published as STI ITR-1310-1
  - Distributed to USAF FIGC mailing list for review
- STEMS Flight Test Evaluation with the NASA F/A-18 HARV published as STI ITR-1310-2 and as WL-TR-97-3002
- Phase II Results published as WL-TR-97-3099 & WL-TR-97-3100
  - Volume I: Maneuver Development Process (-3099)
  - Volume II: Maneuver Catalog (-3100)

MISSION-ORIENTED REQUIREMENTS

- Requirements are based on Mission Task Elements (MTEs) that relate to actual operations
- References to aircraft size are removed
- Allow for multiple response-types
- Provide predicted handling qualities
- Demonstration maneuvers are designed to complement the mission-oriented approach

HANDLING QUALITIES DEMONSTRATION MANEUVERS

- Evaluate *all* aircraft types (military and civil) and mission tasks
- Provide consistent maneuver definitions including desired/adequate performance requirements
- Evaluate total system: flight controls, pilot-vehicle interface, advanced displays and vision aids, etc.
- Provide ultimate check of handling qualities through piloted evaluation

MANEUVER CATEGORIES

- Non-Precision, Non-Aggressive
  - Takeoff, Landing, Waveoff/Go-Around
  - Heading and Altitude Changes
- Non-Precision, Aggressive
  - Air-to-Air Gross Acquisition
- Precision, Non-Aggressive
  - Precision Offset Landing
  - Attitude Capture and Hold
- Precision, Aggressive
  - Air-to-Air Fine Tracking

MANEUVER EVALUATIONS

- Flight Test Evaluations
  - NASA Dryden F/A-18 HARV: STEMS
  - USAF TPS HAVE GAS II: Probe-and-Drogue Refueling
  - USAF TPS HAVE LIMITS: HUD Tracking
  - General aviation aircraft: numerous maneuvers
- Flight Test Reviews
  - Large aircraft flying qualities (TIFS): Precision Offset Landing
  - USAF TPS HAVE CAP: Precision Offset Landing
  - USAF TPS HAVE TRACK: Simulated Aerial Refueling
- Pilot-in-the-Loop Simulation
  - NASA Dryden SR-71 Simulator: Supersonic Maneuver Set
  - McDonnell Douglas: PIO maneuver development

MANEUVER CATALOG

- Final catalog contains 36 maneuvers
  - Flight test evaluations: 18 Maneuvers
  - Simulator evaluations: 16 Maneuvers
  - 5 maneuvers need refinement
- Catalog spans the range of piloted control
- Flight conditions range from post-stall to supersonic, and from takeoff to landing
- Catalog is a living document
  - Revisions and additions are expected as new research is conducted

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EXPOSING PIO

- Demonstration Maneuvers that have produced flight test PIOs
  - Aerial refueling, particularly probe-and-drogue
  - HUD tracking
  - Precision offset landing
- Demonstration Maneuvers that have exposed PIO tendencies
  - Air-to air and air-to-ground fine tracking
  - Attitude captures
  - Gross acquisitions (often expose Category II tendencies)

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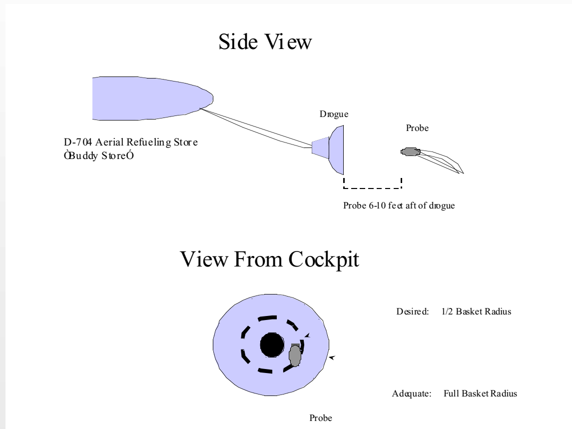
RECENT EVOLUTION OF PROBE-AND-DROGUE REFUELING

- USN F-14 Dual Hydraulic Failure Study (1991)
  - Revealed potential explosive nature of probe-and-drogue refueling task for severely rate limited configurations
  - Formation flying (prior to hook-up) did not expose poor handling qualities
  - Tracking drill devised to "shake out" configurations prior to hook-up
- USAF TPS HAVE GAS (1993)
  - Evaluation of different response-types using probe-and-drogue hook-up task
  - Handling qualities performance requirements (based on number of attempts to achieve three successful hook-ups) were not sufficiently discriminating
- Notice of Change to MIL-STD-1797A (1995)
  - HAVE GAS task with additional requirement to avoid contact with basket webbing for desired performance
- USAF TPS HAVE GAS II (1997)

HAVE GAS II PROGRAM SUMMARY

- USAF TPS Class 96B Test Management Project conducted in spring 1997
- Objective: Identify the task that best reveals aircraft closed-loop probe-and-drogue refueling handling qualities
- Seven flight test sorties: NASA F/A-18 (4 Sorties) and USAF variable stability NT-33A, operated by Calspan, (3 sorties)
- Candidate evaluation tasks: Hook-Up, Tracking, and Aiming Tasks
- Both qualitative and quantitative results clearly indicated that the tracking task best exposed closed-loop handling qualities
- To capture potential problems close-in to the basket, the hook-up task should be performed in concert with the tracking task

DROGUE TRACKING CONFIGURATION



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DROGUE TRACKING TASK FOR PIO

HAVE GAS II

Video Example

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PROBE-AND-DROGUE TASK FOR PIO: CONCLUSIONS

- Probe-and-drogue refueling has exposed all three PIO Categories in flight test
- HAVE GAS II program defined repeatable evaluation tasks based on drogue tracking and hook-ups
- Turbulence can have a significant impact on task performance and should therefore be accounted for in the evaluation process
- A method should be employed to verify drogue tracking distance (chase plane, differential GPS, etc.)

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HUD TRACKING TASKS FOR PIO

- Recent Experience
  - USAF TPS HAVE LIMITS
  - McDonnell Douglas ground simulation comparison study
  - STI development of pilot evaluation tool (PASS) using sum-of-sines tracking tasks
  - HAI PIO simulations on LAMARS using discrete (“step-and-ramp,” “Calspan” or “SAAB”) tracking tasks
- Sum-of-Sines effective for identifying pilot dynamics and PIO tendencies, especially Category I
- Discrete Tracking effective for identifying PIO tendencies, especially Category II

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HUD TRACKING TASKS FOR PIO

HAVE LIMITS

Video Example

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HUD TRACKING TASKS FOR PIO: CONCLUSIONS

- There may be initial pilot reluctance to sum-of-sines task
- Discrete tracking is most effective as a two-axis task
  - Reduces pilot "learning"
  - Exposes both pitch and roll problems
- Verbal readouts not effective
  - Introduces undesired variability with commands
  - Must be single-axis only
  - Potential for pilot confusion over command values
  - No way to monitor tracking performance
  - Must be steps only, since "ramps" cannot be introduced verbally

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DEMONSTRATION MANEUVERS FOR PIO

- Need for dedicated PIO Demonstration Maneuvers
  - PIO is not an operational event
  - PIO testing should be distinct from handling qualities
  - Some testing will be inconsistent with operational testing (e.g., HUD tracking or close formation with a transport)
- Additional candidate PIO Demonstration Maneuvers
  - SAAB Klonk method
  - HQDT
  - Rapid attitude captures
  - Others?

Session VI

T45TS

Boeing T45 Ground Handling Characteristics NASA Dryden Workshop

Jim Reinsberg

Principal Technical Specialist

T45TS Aerodynamics, Flying Qualities

The Boeing Company

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6-8 Apr 99

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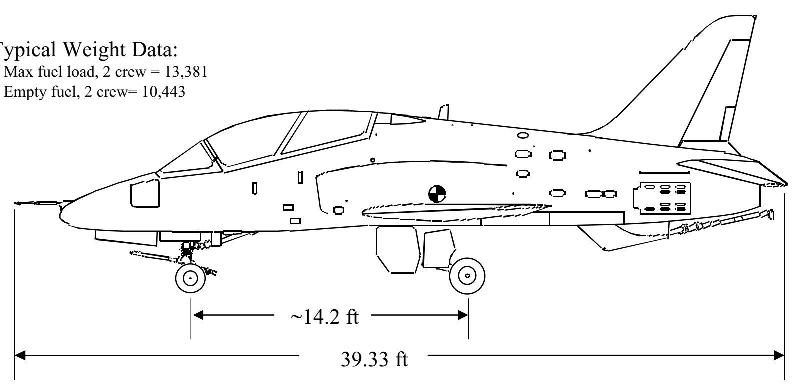
T45 Aircraft Description Derived from BaE Hawk

Typical Weight Data:
> Max fuel load, 2 crew = 13,381
> Empty fuel, 2 crew= 10,443



Key aircraft components:
> ~12% of weight on nose landing gear
> Single chambered, semi-levered main landing gear
> Single chambered, cantilevered nose landing gear (2 tires)
> 20 deg/sec nose wheel steering (NWS) - 12 deg defl max
> Reversible, mechanical rudder
> Hydraulic powered aileron, stabilator.
> Limited Yaw Damper Control (YDC)

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Summary of T45 Ground Handling Issue

Directional control issues have been with the T45 since 1989. This is a basic airframe issue. Multiple "Triggers" such as cross-winds, inadvertent brake/NWS/rudder inputs, blown tire, aggressive corrections, etc. create a control problem which is amplified by "Sustainers" such as landing gear dynamics, brake sensitivity and feel, roll/yaw coupling, lateral acceleration cues, etc. Over the years many attempts and studies have been undertaken to improve basic airframe handling characteristics with some success. But fixes are not easy or "cheap". The lack of a good ground handling METRIC has dampened the enthusiasm to flight test "potential fixes".

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BA/USN Efforts Toward Resolution

Solutions Investigated With Mixed Success

- Nov 89 Established SA-4A during DT-IIA:
  - "Directional pilot induced oscillations during landing rollout."
- Nov 90 Developed current production NWS system
  - Full time NWS cleared "PIO" yellow sheet SA-4A
  - Entered Fleet Aug 92
- May 93 Established SA-162 during DT-II:
  - "Overly sensitive directional control characteristics during landing rollout."
- Dec 93 Developed 1st industry ground handling PIO metric
  - Provided a "yardstick" for predicting effectiveness of modifications
- Mar 94 ADR data @ KNAS supported PIO metric
- Mar 94 Started flight evaluation of higher rate NWS system
  - Improved handling but PIO susceptibility remained
- Jun 94 Joint USN/MDA "PIO team" formed to explore causes and solutions
- Sep 94 Recommended fix of high gain yaw damping with higher rate NWS
- Nov 95 Started flight evaluation of "PIO team" recommended fix
  - Concluded improvements not adequate for production
  - Identified objectionable ground handling other than PIO
- Jan 97 NAVAIR recommended assessment by outside company
- Aug 98 Started independent assessment with STI, subvendor to BA

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Boeing Criteria for Ground PIO Susceptibility

- **Applied Mil STD criteria for longitudinal PIO (Ralph Smith).**
  - **Showed this to be a good predictor of directional PIO tendencies with:**
    - **> Frequency response of flight test data**
    - **> Six degree of freedom (6-DOF) analysis with 0.25 sec time delay pilot model**
- **MDA experience at this time:**
  - **10 PA landings were analyzed – included a variety of pilots, crosswinds, and braking tasks.**
    - **> Ny at pilot and yaw rate (R) considered most significant control parameters**
    - **> Bode plots: 0.6 Hz control from Ny feedback, 1.0 Hz control from R feedback**
  - **A015 landing rollout PIO shows pilot “responding” to Ny**
- **Criteria successfully predicted higher rate NWS would not reduce PIO potential.**
- **Employed as metric for joint USN/Boeing PIO Susceptibility team**
  - **Goal: Achieve F-18 Ny phase response.**
  - **Identified 50 potential causes. 8 most promising showed no single or combined root cause.**
  - **Analyzed 3 augmented control solutions:**
    - **> R + Ny feedback to NWS, R command, and R feedback to rudder**
- **R feedback to rudder met F-18 Ny phase criteria.**

6-8 Apr 99

Improved, high rate PWM NWS and YDC-10 approved for flight test.

T45TS

Results Of YDC-10 Flight Test Program

Steering Control Electronic Set (SCES) 1.4

- Allowed testing of production and “test” software with a bit flag change.
- Production T45 NWS software:
  - Bang-bang controller, 20 deg/sec max no-load rate
  - Turn-on at 0.75 deg error, turn-off at 0.5 deg error.
  - Low gain steering: linear slope, 2.5 inches of pedal -> 12 deg of NWS
- Pulse Width Modulation (PWM) software:
  - Still a bang-bang controller, but
    - > 5 discrete no-load rates, from 8 deg/sec to 52 deg/sec
    - > Uses “look-ahead” to determine best control speed
    - > Narrows turn-on/turn-off threshold when pedals moving
    - > Variety of pedal -> NWS schedules available

NOTE: PWM also required a hydraulic supply orifice change to achieve higher no-load rate.

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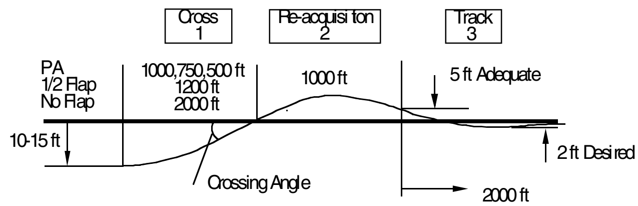
Results Of YDC-10 Flight Test Program

Centerline Crossing Task



CROSS
- Low gain and low predictability
- Significant variations in crossing angle
- YDC tends to washout initial input

RE-ACQUISITION
- High gain, high accelerations/rates
- Susceptible to "roll/yaw"
- Steeper x-ing angle, harder task, prone to centerline overshoot

TRACK
- High gain, low Ny, moderate yaw rate
- Performance degraded if Phase 2 overshoots desired criteria

Combined with other variations (weight, crosswind, inadvertent differential braking), significant run-to-run variations in task difficulty can occur.

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Results Of YDC-10 Flight Test Program

- FREQUENCY DOMAIN ANALYSIS
  - Predicted reductions in Ny phase lag were achieved
    - > Only for small inputs (~25%) due to yaw damper saturation
  - High rate NWS had no effect on Ny or R phase lag
  - Centerline x-ing maneuver did produce PIOs during Re-acquisition and Tracking
    - > ONLY with non-optimum YDC feedback gain
    - > Re-acquisition PIOs : High Ny -> roll/yaw
    - > Tracking PIOs : Low Ny -> often ignored in pilot comments
- PILOT COMMENTS
  - PIO ratings slightly reduced with YDC/PWM.
  - Significant factors other that phase lag influencing the pilot
    - > Velocity vector loosely coupled to nose
    - > Roll opposite yaw - "leans"
    - > Inadvertent NWS inputs
    - > Insufficient brake pedal (force) feedback
    - > Rudder pedal mechanical characteristics
    - > Crosswinds

CONCLUSIONS: Incremental improvement for small pedal inputs only, and would not close yellow sheet SA-162.

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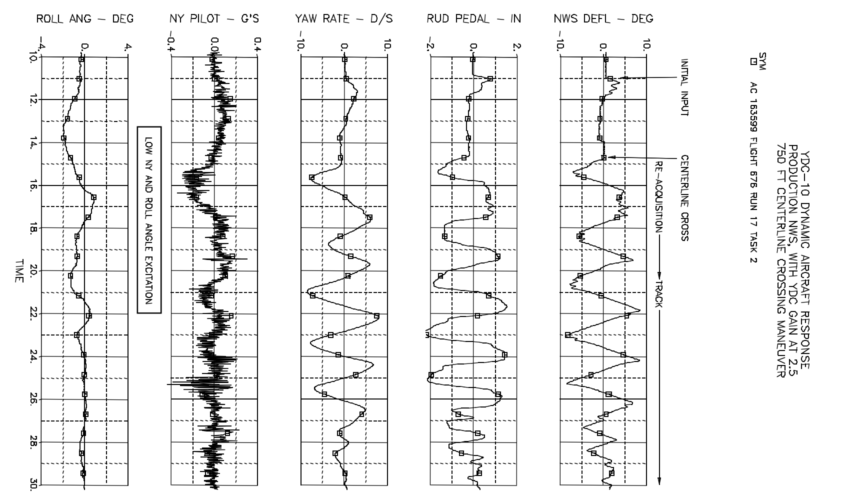
Results Of YDC-10 Flight Test Program



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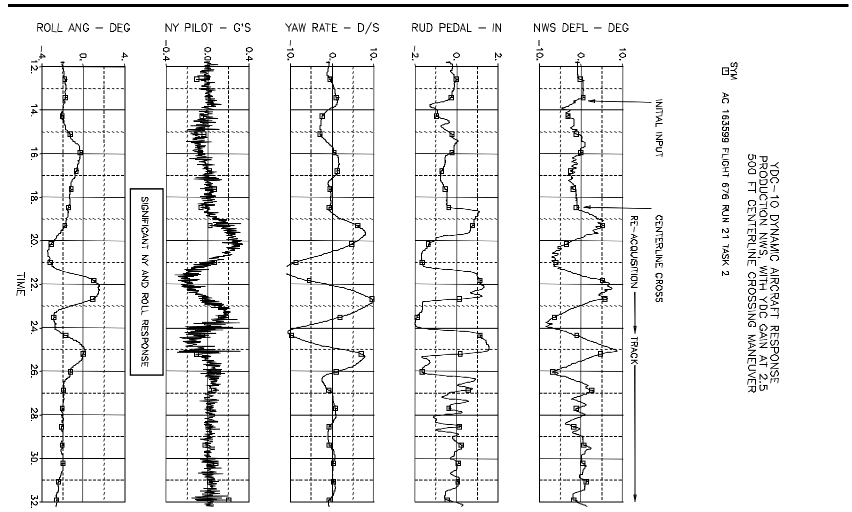
Results Of YDC-10 Flight Test Program



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NASA LaRC Analysis of T45 Tires

- **METHOD:**
  - **Used Low speed Tire Test Vehicle (LTTV) to measure cornering performance of nose and main tires under full scale, realistic surface conditions.**
    - **> Max vertical load 6000 lb**
    - **> Max tire yaw angle 90 deg**
    - **> Max speed 60 mph**
  - **Varied tire pressure (field, carrier), vertical load and skid angle.**
  - **Nose tire is very under-loaded at 300-900 lb per tire (5-6% vs. design 32%).**
  - **LTTV data validated by flight test trajectory matching.**

- **CONCLUSION:**
  - **Main tire cornering stiffness <u>less</u> than modeled by 13-44%, depending on normal load.**
  - **Main tire cornering stiffness reduction with normal load more than currently modeled.**
  - **Nose tire cornering stiffness <u>more</u> than modeled by 6-19%, depending on normal load.**

A ground handling assessment REQUIRES accurate tire data under realistic surface conditions. The LTTV proved to be a rapid and economical tool for gathering T45 tire data. Other NASA facilities exist for tires with greater vertical loadings.

6-8 Apr 99

T45TS

Independent Assessment Contract With STI

- Objective and Product:
  - Analytical assessment by Systems Technology Incorporated (STI)
  - Recommend procedures and/or aircraft modifications with the potential to minimize or eliminate undesirable landing rollout characteristics.
  - Feasible recommendations will likely require additional research and flight evaluation by USN/BA team prior to production consideration

- Tasks:
  - Review past efforts
  - Examine basic aircraft design issues
  - Recommend a way forward

- Status:

7 Feb 98	-	USN issued RFP to Boeing (BA)
21 Apr 98	-	BA selected STI as winning subvendor
21 Jul 98	-	USN/BA complete contract negotiations
20 Aug 98	-	Kickoff meeting in STL. BA, STI & NAVAIR (15 month contract)
16 Nov 98	-	First quarterly review
18 Feb 99	-	Second quarterly review
15-19 Feb 99	-	First flight simulation

6-8 Apr 99

T45TS

Independent Assessment
Contract With STI
Status After First Flight Simulation

- **NASA LARC tire data incorporated into all 6-DOF models.**
- **Analysis of flight test data suggest that heading angle feedback is the primary pilot control mechanism.**
- **Boeing 6-DOF and STI linear model have been benchmarked to flight test data.**
- **STI Linear model analysis shows that the T45 –**
  - **has an oversteer characteristic (tire cornering stiffness is key)**
  - **has a critical speed, above which the vehicle has an unstable pole (~ 60 kts).**
- **The understeer gradient UG may be a reliable metric for PIO potential**

$$UG \; [deg/g] = 32.17*57.3*\{(m/l)*[(b/Y_{\alpha f}) - (a/Y_{\alpha r})]\}$$

m	= vehicle mass	[slugs]
a	= distance from front tire to cg	[ft]
b	= distance from rear tire to cg	[ft]
l	= distance from front to rear tire (l=a+b)	[ft]
$Y_{\alpha f}$	= front axle "aero+tire+.." cornering coefficient	[lbf/rad]
$Y_{\alpha r}$	= rear axle "aero+tire+.." cornering coefficient	[lbf/rad]

6-8 Apr 99

T45TS

Independent Assessment
Contract With STI
Status After First Flight Simulation

- Maneuvers used during first simulation:
  - Constant radius turn circle (2000 ft)
  - Maximum heading capture and stabilization (aggressive)
  - Heading capture and hold (instruments only - no visual)
  - Heading angle sum-of-sines tracking (instruments only - no visual)
  - Runway centerline tracking with crosswind gust disturbance
- Aircraft parameters varied during first simulation:
  - Fuel (empty, 65% full)
  - Aircraft understeer gradient, UG
  - Nose wheel steering actuator model (production and "ideal")
- Preliminary findings:
  - Fixed base simulation: not perfect, but we're working on it
  - "Ideal" actuator model: most effect on fine tracking, not PIO
  - Turn circles show a break in roll vs. Ny at 0.2 g's (approx 2 deg roll)
  - HQR and PIO ratings track understeer gradient UG
  - A 2 point HQR/PIO reduction may be possible with a tire change

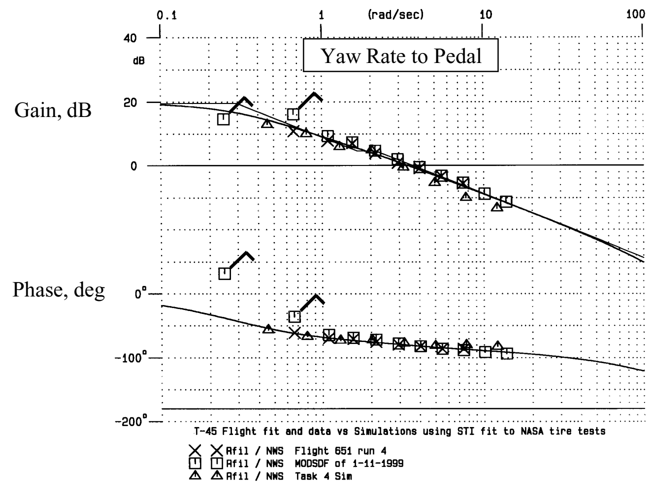
6-8 Apr 99

Independent Assessment Contract With STI

Status After First Flight Simulation

T45TS

Excellent agreement between flight test, flight simulation and Boeing 6-dof (MODSDF)



Low Power in Flight Test Data

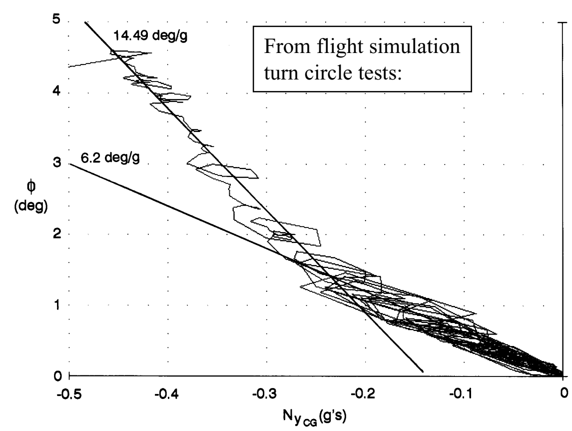
6-8 Apr 99

Independent Assessment Contract With STI

Status After First Flight Simulation

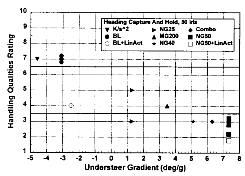
T45TS

From flight test: More than 2 deg of roll was consistently remarked as “very uncomfortable”. Below 2 deg of roll, it was often ignored.

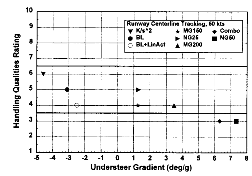


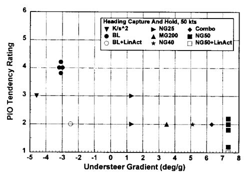
6-8 Apr 99

Independent Assessment
Contract With STI
Status After First Flight Simulation



Heading Capture and Hold:
> projected HUD only
> 10 deg heading change





Runway Centerline Tracking:
> full visual scene
> random x-winds during tracking

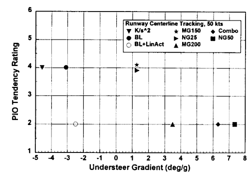


Figure 1. HQR and PIOR versus Understeer Gradient for the Heading Capture and Hold Task

Figure 3. HQR and PIOR versus Understeer Gradient for the Runway Centerline Tracking Task

6-8 Apr 99

Independent Assessment
Contract With STI
Future Efforts

- Refine Boeing flight simulation
  - Adjust seat/pedal/heel-rest to T45 spec
- Pilot-vehicle analysis:
  - Acquire flight test data from dissimilar aircraft
  - Complete pilot-vehicle analysis of ground handling dynamics:
    - > Ergonomics (braking, steering crossover)
    - > Control sensitivity and magnitude
    - > Crosswinds
- Refine tasks/metrics to quantify expected improvements
  - Define new, or modify existing tasks.
  - Quantify possible “improvements” in flight simulation
- Present final report/recommendations: November, 99

6-8 Apr 99

EXTRACTION OF PILOT-VEHICLE CHARACTERISTICS FROM FLIGHT DATA IN THE PRESENCE OF RATE LIMITING

David H. Klyde
dklyde@systemstech.com
Systems Technology, Inc.

David G. Mitchell
Hoh Aeronautics, Inc.

Pilot-Induced Oscillation Research:
The Status at the End of the Century
NASA Dryden Flight Research Center
6-8 April 1999

PRESENTATION OUTLINE

- Program Overview
- Background
  - Category II PIOs
  - Airplane Bandwidth/Phase Delay Criteria
- F-14 Dual Hydraulic Failure Flight Test Program
  - Flight Test Data Description
  - Flight Test Data Analyses
- Conclusions

PROGRAM OVERVIEW

- Work performed by Systems Technology, Inc. (STI) under a subcontract from Hoh Aeronautics, Inc. (HAI)
- Part of a HAI Phase II SBIR with the Air Vehicles Directorate of the Air Force Research Laboratory
- Air Force Project Engineer - Thomas J. Cord
- F-14 flight data provided by Naval Air Warfare Center, Aircraft Division

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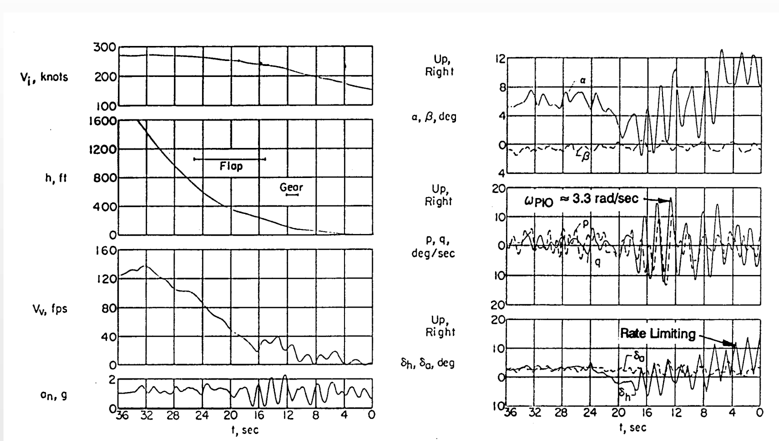
TIME HISTORY OF THE X-15 LANDING/FLARE PIO



Ref. NASA TN D-1057

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CATEGORY II PIOs

- Essentially nonlinear pilot-vehicle system oscillations with amplitudes well into the range where rate and/or position limits become dominant
- Transitional category between Category I and the most general, nonlinear Category III PIOs
- Most common jump-resonant, limit-cycle, PIO event
- Intrinsically severe PIOs

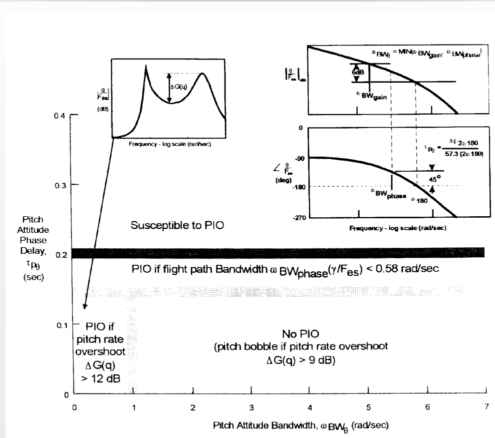
CATEGORY II ISSUES

- Presence of rate limiting and other nonlinearities result in a *Frequency* and *Amplitude* dependence
- There are, therefore, a task dependent family of solutions that will determine PIO susceptibility
- Rate and/or position limiting within a closed-loop structure will disrupt the aircraft augmentation as the limiter becomes active
- Criteria will be inherently more complicated in their application
- Ready applicability of criteria may imply a need for specific software applications

CATEGORY II FLIGHT DATA

- All candidate criteria are tentative until validated with flight data (qualitative & quantitative)
- Until recently available flight data has been extremely limited and incomplete (essentially time histories from flight test of developmental aircraft)
- HAVE LIMITS (USAF TPS Class 96B)
  - Configurations flown with variable stability NT-33A
  - Reference AFFTC-TR-97-12 (approved for public release)
- USAF TIFS Study
  - Parallel HAVE LIMITS with large aircraft configurations

BANDWIDTH/PHASE DELAY REQUIREMENTS



BANDWIDTH/PHASE DELAY

- Use flight derived frequency response (nonlinearities included) to compute Bandwidth (ω_{BW}) and Phase Delay (τ_p) parameters for a variety of input amplitude levels
- Assume linear requirements apply to nonlinear (quasi-linear) configurations at each input amplitude
- A Bandwidth/Phase Delay locus that is a function of input amplitude is overlaid on the linear requirements to define PIO-prone regions
- The input amplitude conditions (A_i) corresponding to the boundary crossing of the [τ_p, ω_{BW}](A_i) locus indicates a critical region for possible onset of Category II PIO

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BANDWIDTH/PHASE DELAY (concluded)

- The transition from a phase margin bandwidth condition to a gain margin bandwidth condition can be indicative of a Category II jump resonance phenomenon
- A systematic approach to specify pilot input magnitude for conducting frequency sweeps is needed
- Drops in coherence occur whenever power is present in the output that does not correspond to the PVS input, such as pilot-induced noise (remnant), sampling harmonics, and nonlinearities
- Analysis of available data often indicates a reduction in describing function coherence in the neighborhood of the onset or saturation frequency of the rate limiter

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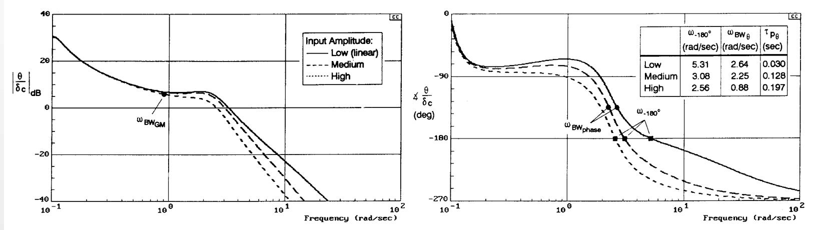
DESCRIBING FUNCTION VARIATIONS WITH INPUT AMPLITUDE



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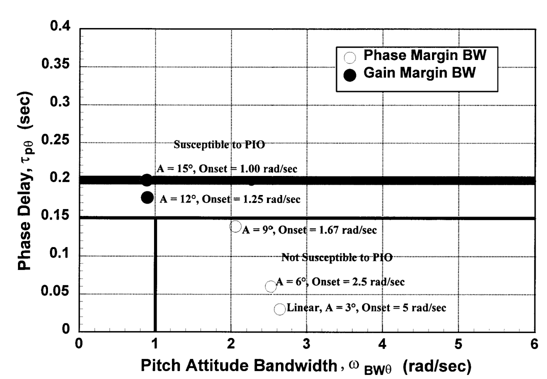
BANDWIDTH/PHASE DELAY INPUT AMPLITUDE SENSITIVITY



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F-14 DUAL HYDRAULIC FAILURE FLIGHT TEST PROGRAM

- Navy flight test program was conducted from 10/90 to 3/91.
- The back-up flight control module (BUFCM) was evaluated for in-flight refueling and landing.
- Maximum stabilator rates were 10 and 5 deg/sec for BUFCM-HIGH and BUFCM-LOW modes, respectively.
- Aircraft demonstrated good handling in formation flight.
- A number of PIOs were encountered during in-flight refueling, drogue tracking, and offset field landings.
- An excellent PIO database was inadvertently created.

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FLIGHT TEST DATA ANALYSES

- Flight Test Data Description
- Example Time Histories
- Identification of Stick Dynamics
- Effects of Rate Limiting
- Identification of PIO Frequency and Task Bandwidth
- Airplane Bandwidth/Phase Delay Assessments

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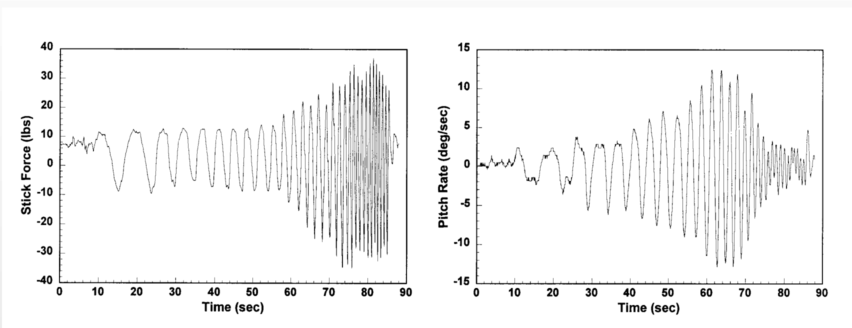
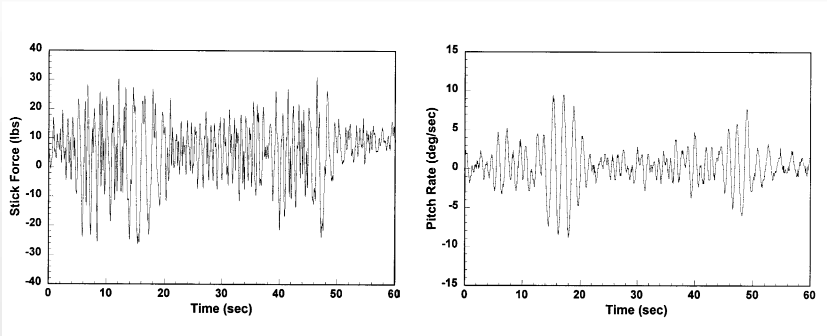
FLIGHT TEST DATA DESCRIPTION

- High quality time history data for:
  - 7 frequency sweeps
  - 8 drogue hook-ups
  - 2 drogue tracking runs
  - 1 field offset landing
- Runs were characterized by:
  - Aircraft configuration: wing sweep, gear and flap positions
  - Flight condition: altitude, airspeed, Mach number
  - FC mode: SAS On, SAS Off, BUFCM-HIGH, BUFCM-LOW

BUFCM-HIGH FREQUENCY SWEEP TIME HISTORIES



BUFCM-HIGH DROGUE TRACKING TIME HISTORIES



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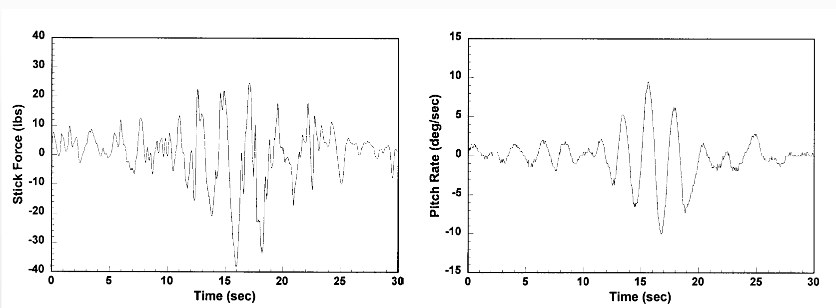
BUFCM-HIGH DROGUE HOOK-UP TIME HISTORIES



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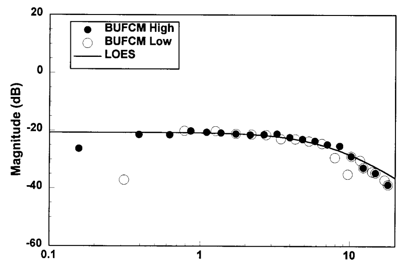
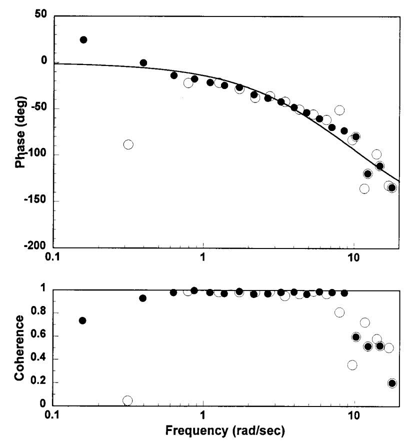
LONGITUDINAL STICK DYNAMICS





$$LOES = \frac{\delta_{LON}}{F_{LON}} = \frac{42.7e^{-.03}}{a + 5.46\,a + 83.15}$$

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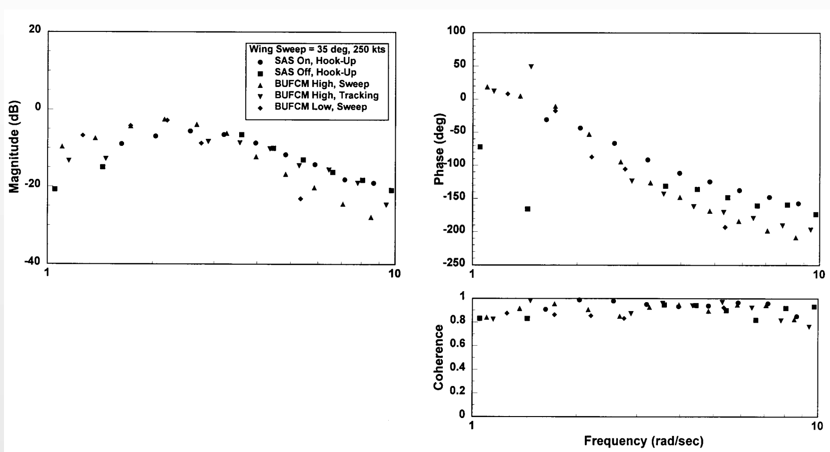
EFFECTS OF RATE LIMITING ON q/F_{LON}



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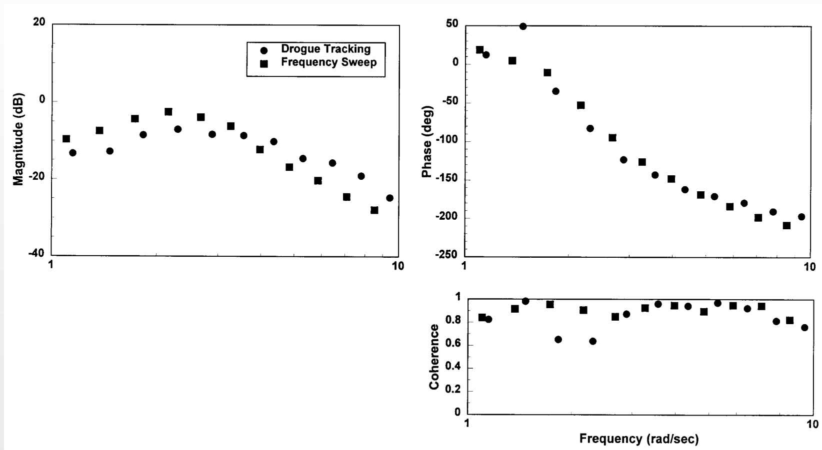
BUFCM-HIGH
q/F_{LON} CASE COMPARISON



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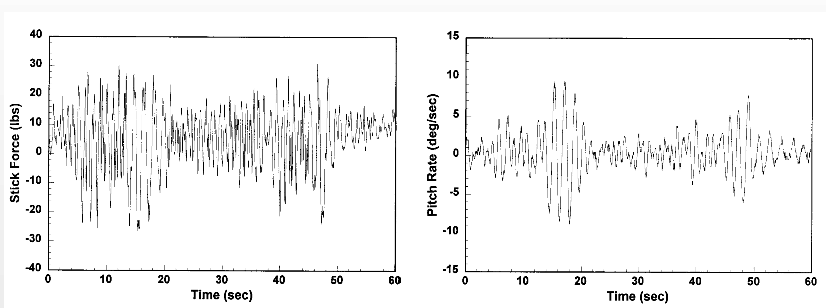
BUFCM-HIGH DROGUE
TRACKING TIME HISTORIES



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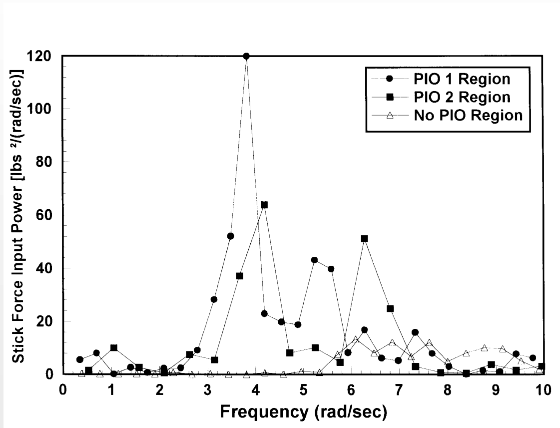
PILOT INPUT PSD FOR BUFCM-HIGH DROGUE TRACKING



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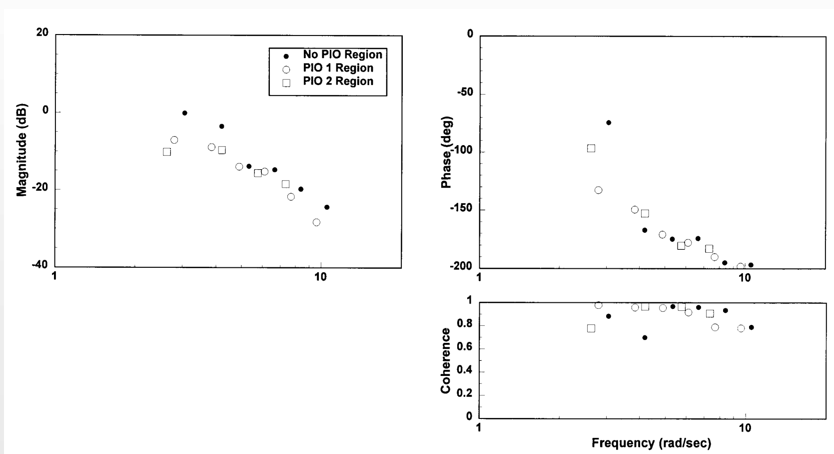
q/FLON FREQUENCY RESPONSES FOR BUFCM-HIGH DROGUE TRACKING



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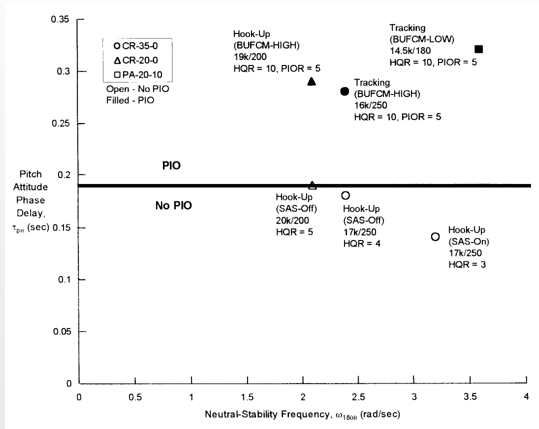
PIO PHASE DELAY REQUIREMENT



CONCLUSIONS

- Frequency domain analysis techniques were successfully applied to flight test data to obtain describing functions in the presence of rate limiting.
- Results display the expected magnitude reduction, significant additional phase lag, and input amplitude sensitivity associated with rate limiting.
- Frequency sweeps and drogue tracking runs allowed for best extraction of PVS characteristics.

CONCLUSIONS

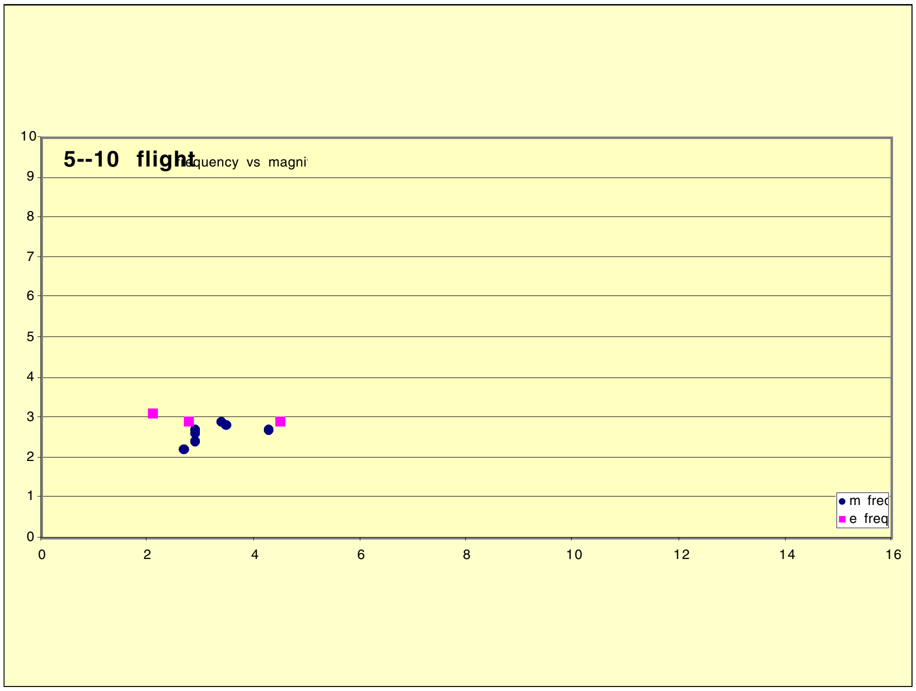
- PIO frequencies and task bandwidths were identified from the pilot input PSDs.
- Excessive phase delay due to rate limiting led to PIO for both drogue hook-up and tracking tasks.
- Results from the analysis of the flight test data support the application of Bandwidth/Phase Delay criteria for the prevention of PIO.

COMPARISON OF PIO SEVERITY FROM FLIGHT AND SIMULATION

Thomas J. Cord
AFMC/AFRL/VAAD
NASA PIO WORKSHOP
APRIL 1999

PIO FREQUENCY AND MAGNITUDE

- PILOT CONSISTENCY
  - FLIGHT
  - SIMULATION


5--10 flight
frequency vs magni
m freq
e freq
10
9
8
7
6
5
4
3
2
1
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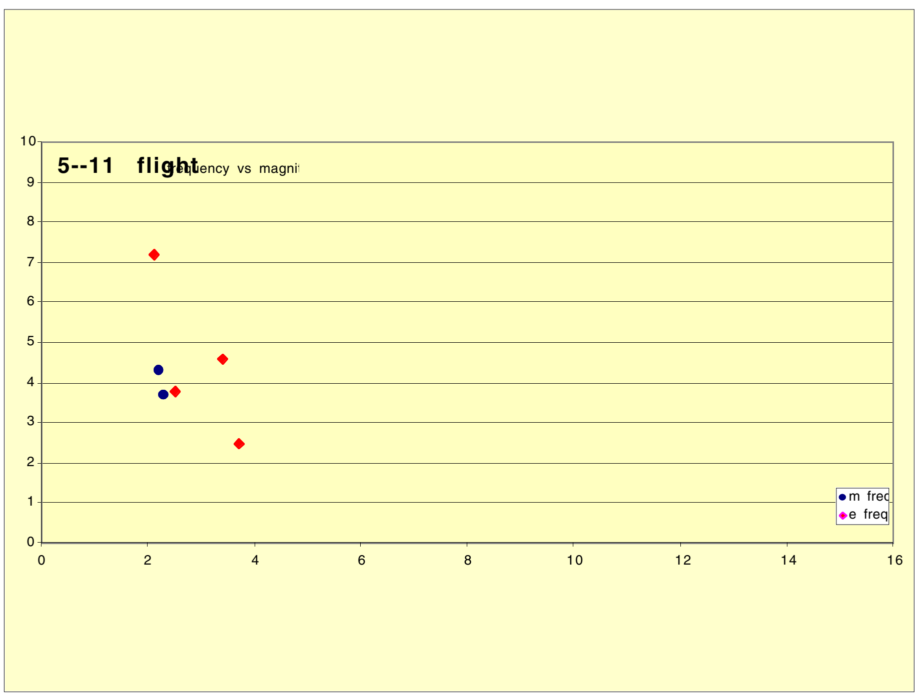
16


5--11 flight
frequency vs magni
m freq
e freq
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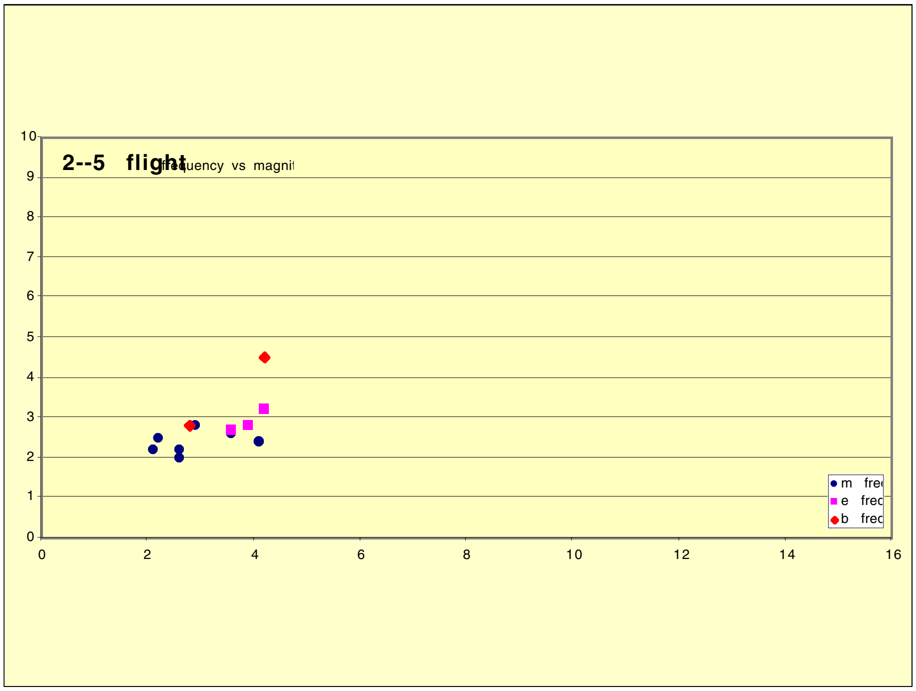
2--5 flight
frequency vs magni
m fre
e fre
b fre
0
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4
5
6
7
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9
10
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2
4
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8
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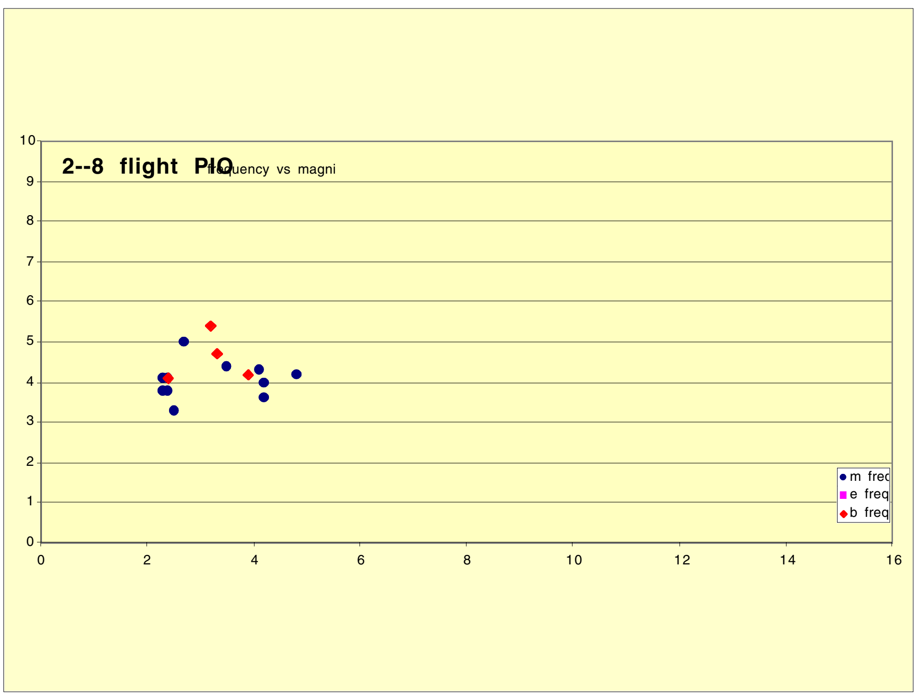
14
16


2--8 flight PIO
frequency vs magni
m freq
e freq
b freq
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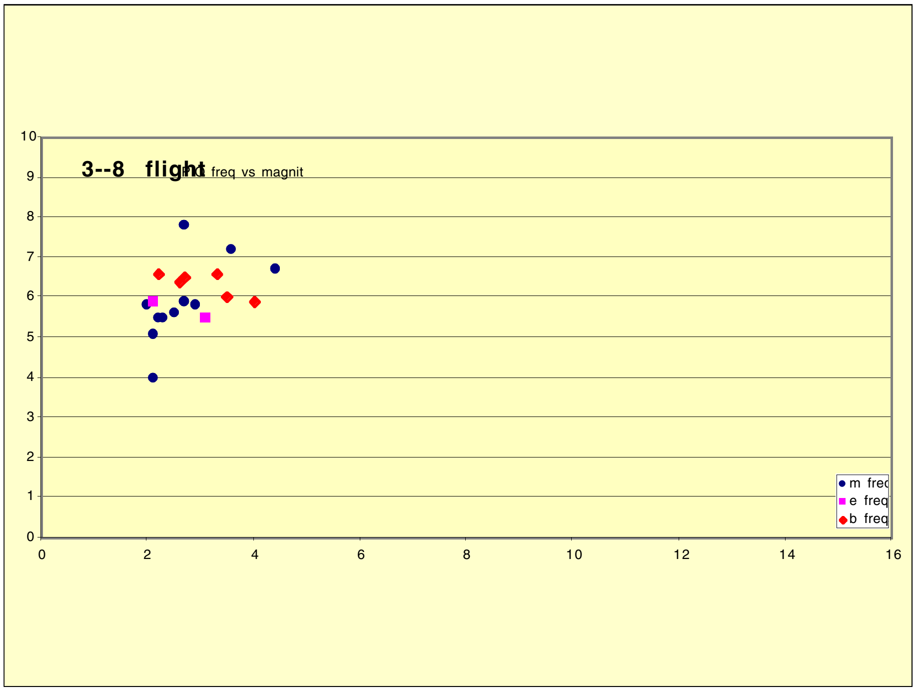
3--8 flight
PTO freq vs magnit
m freq
e freq
b freq
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1
2
3
4
5
6
7
8
9
10
0
2
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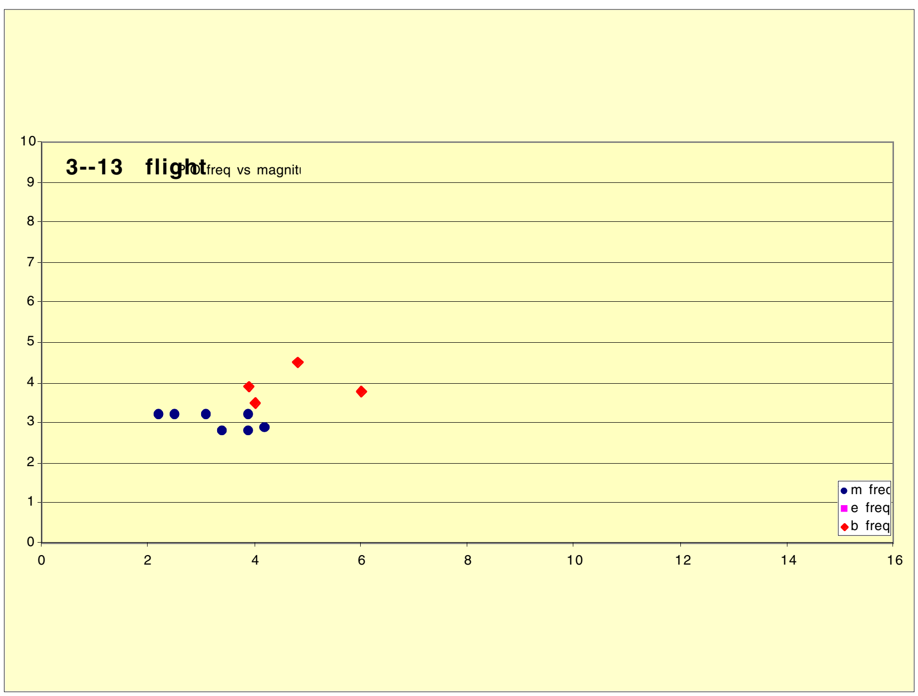
3--13 flight
PTO freq vs magnit
m freq
e freq
b freq
0
1
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2
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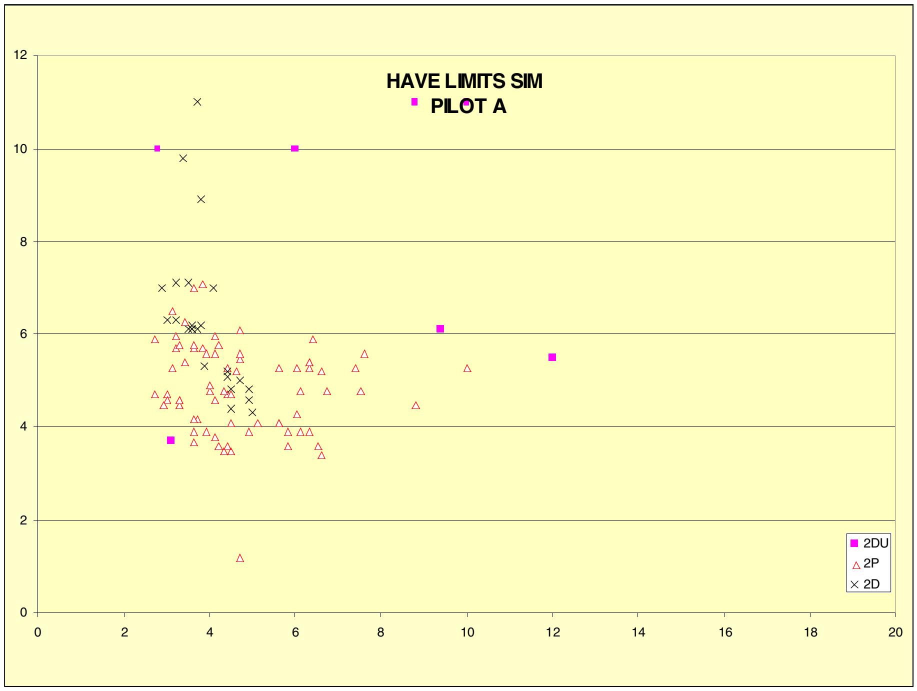
HAVE LIMITS SIM
PILOT A
12
10
8
6
4
2
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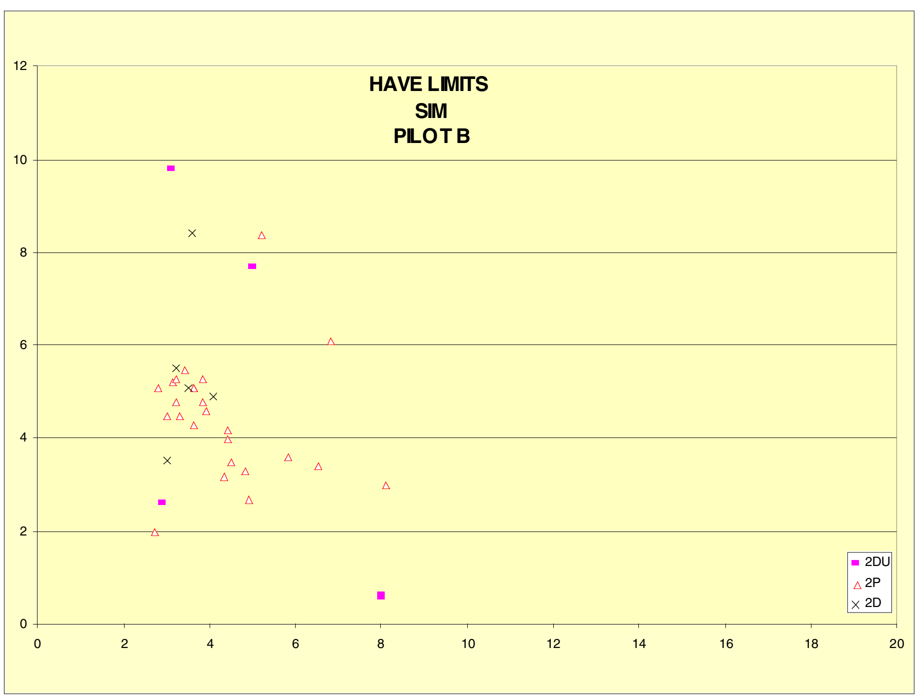
8
10
12
14
16
18
20
2DU
2P
2D


HAVE LIMITS
SIM
PILOT B
12
10
8
6
4
2
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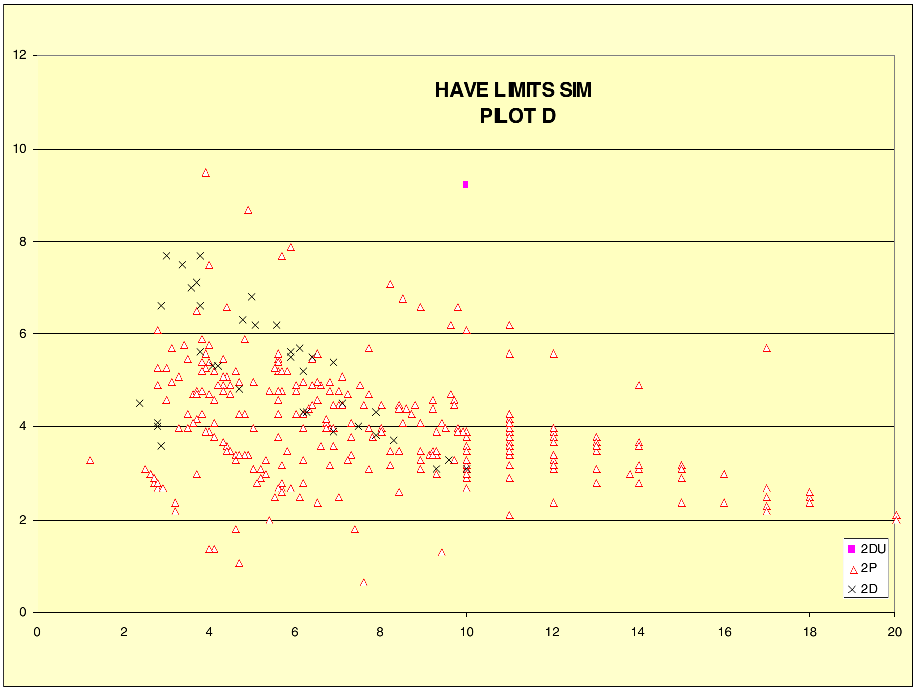
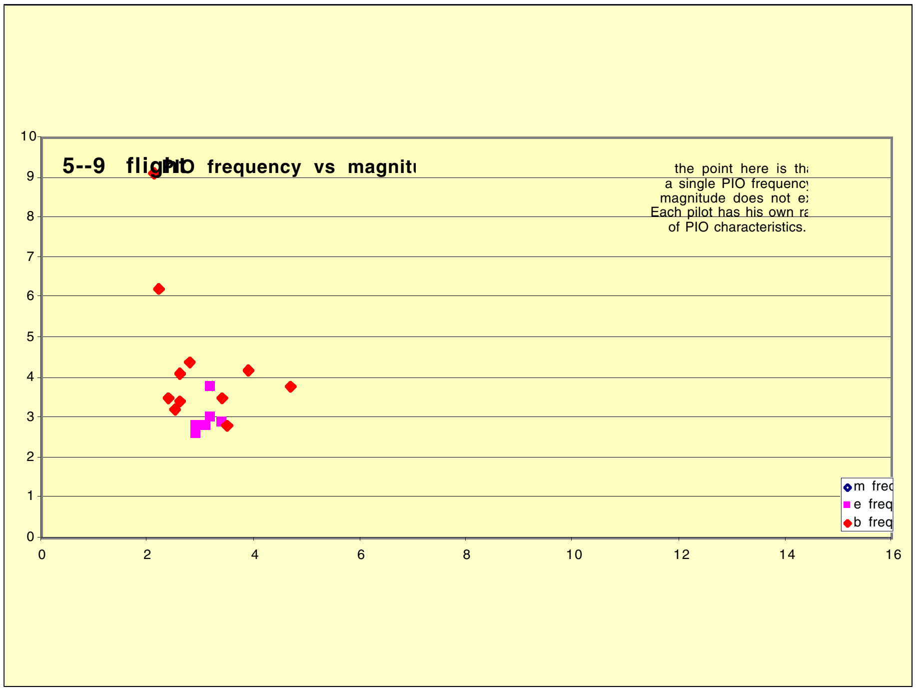
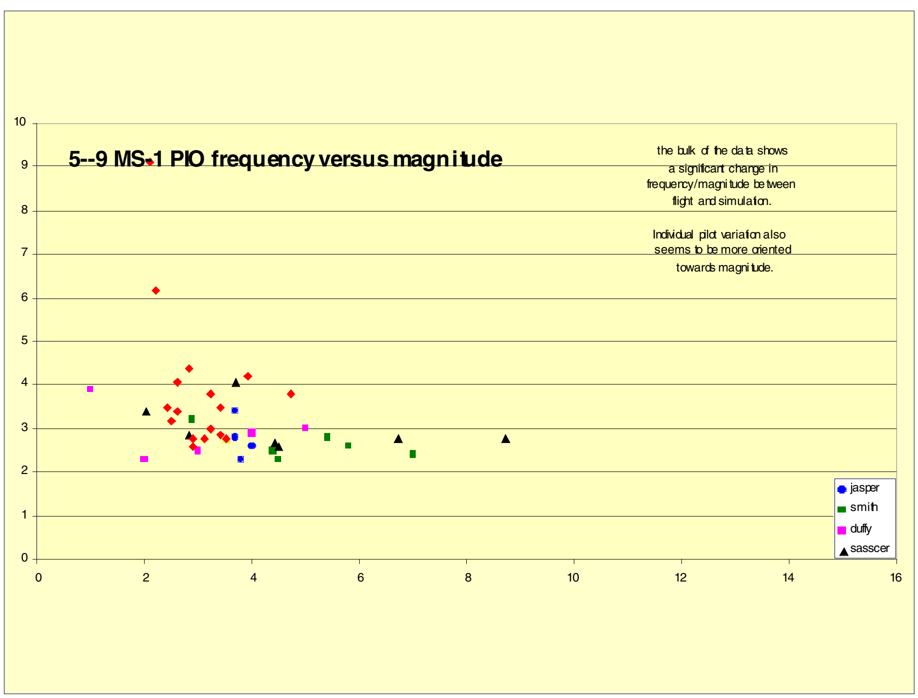
2
4
6
8
10
12
14
16
18
20
2DU
2P
2D

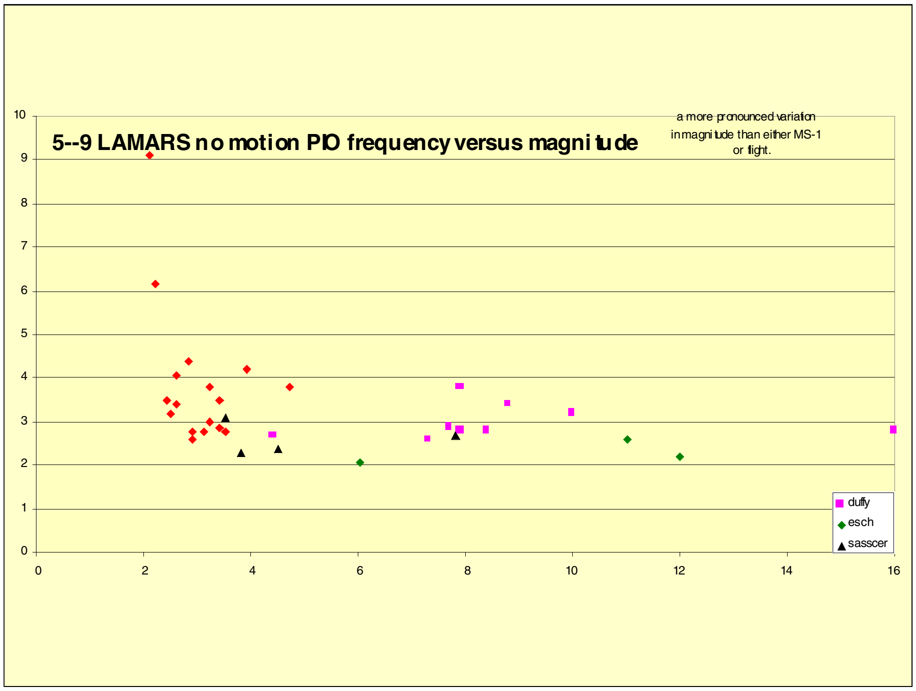


PIO FREQUENCY AND MAGNITUDE

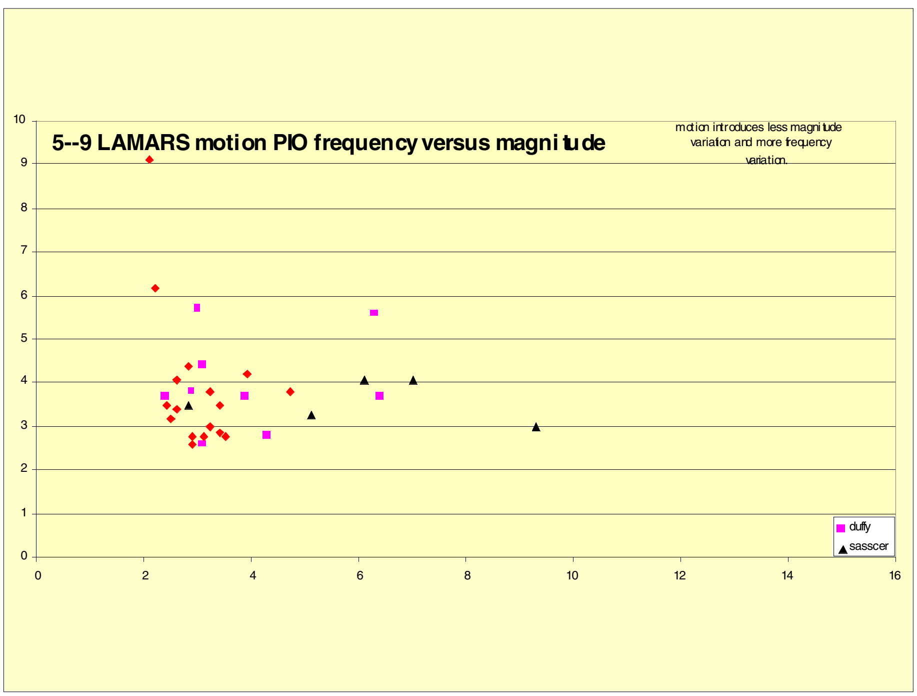
- EFFECT OF SIMULATION ENVIRONMENT


5--9 flight PIO frequency vs magnitu
the point here is tha
a single PIO frequency
magnitude does not ex
Each pilot has his own ra
of PIO characteristics.
m freq
e freq
b freq


5--9 MS-1 PIO frequency versus magnitude
the bulk of the data shows
a significant change in
frequency/magnitude between
flight and simulation.
Individual pilot variation also
seems to be more oriented
towards magnitude.
jasper
smith
duffy
sasscer



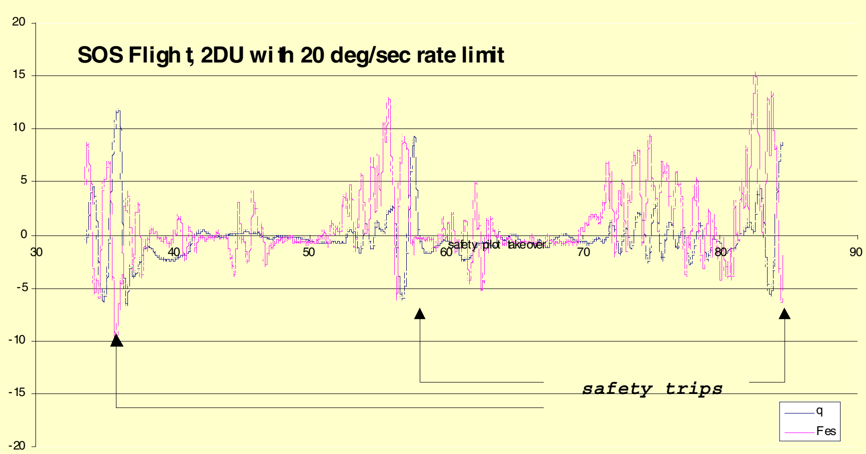
5--9 LAMARS no motion PIO frequency versus magnitude
a more pronounced variation in magnitude than either MS-1 or flight.
duffy
esch
sasscer
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
14
16

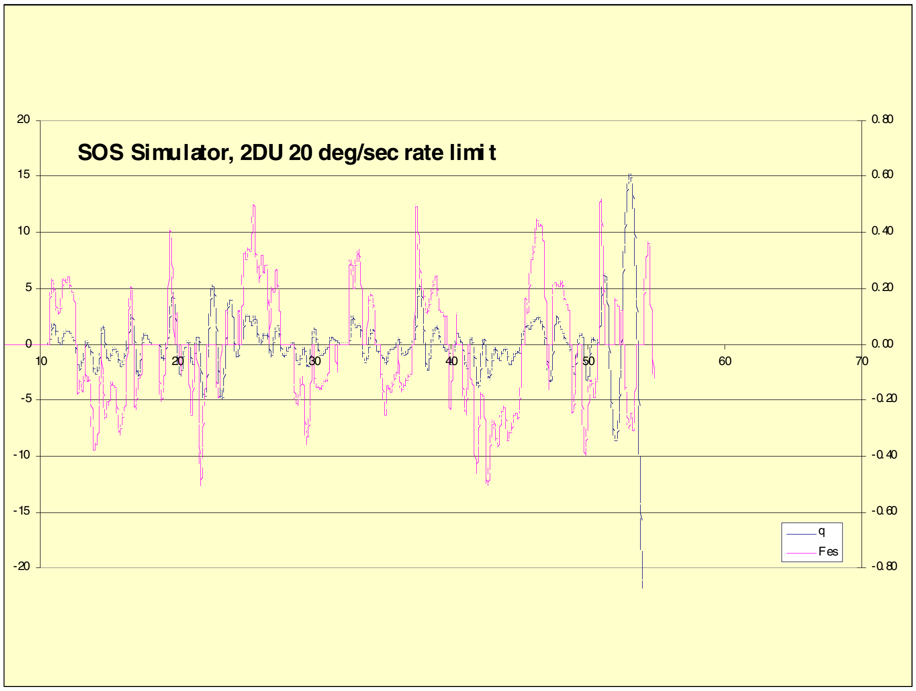


5--9 LAMARS motion PIO frequency versus magnitude
motion introduces less magnitude variation and more frequency variation.
duffy
sasscer
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
14
16

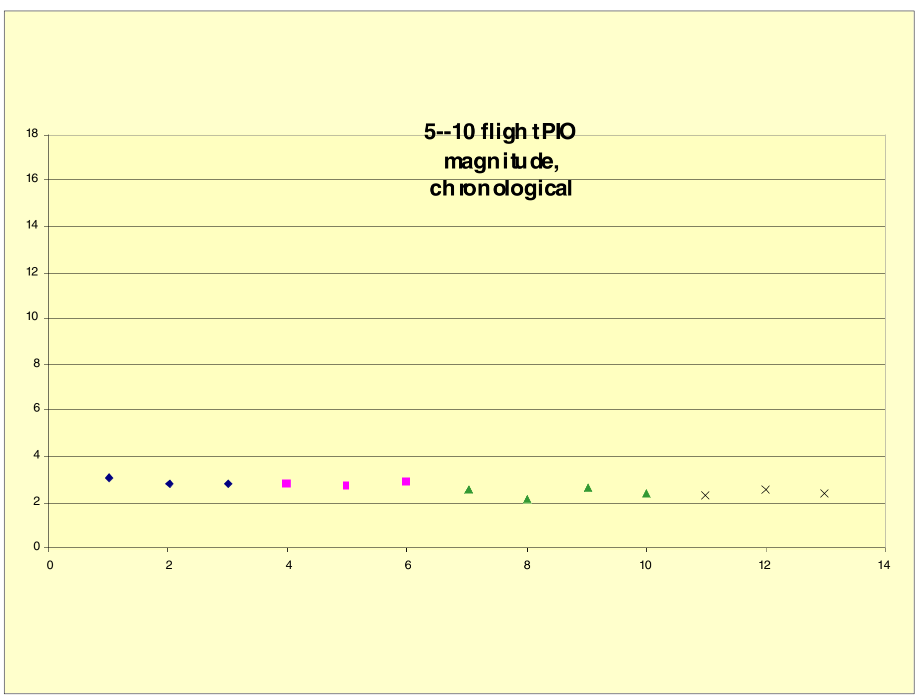
TIME HISTORY ILLUSTRATIONS

- GROWTH OF PIO MAGNITUDE
- INFLUENCE OF SAFETY PILOT

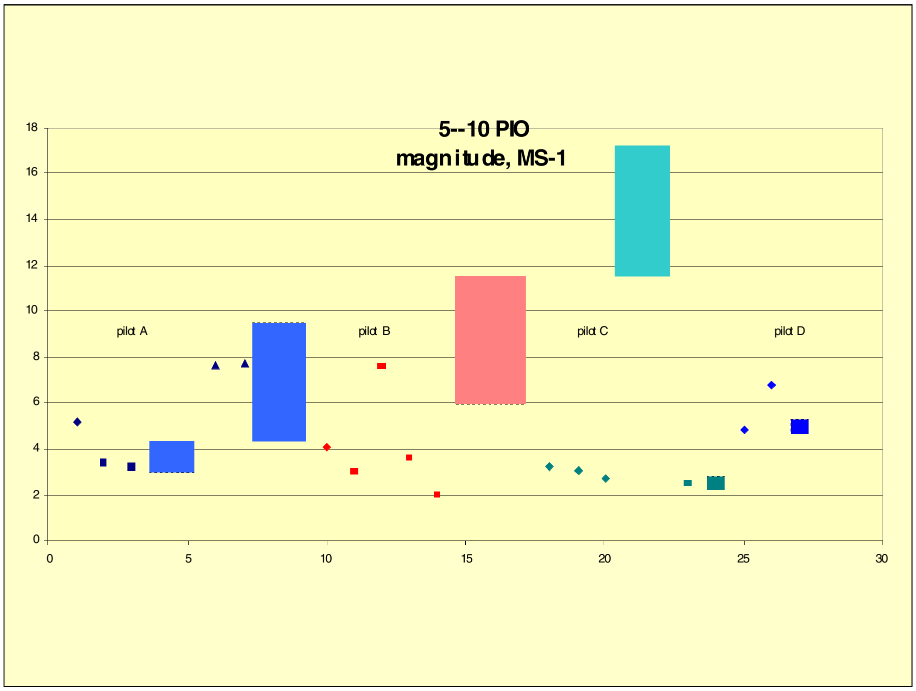


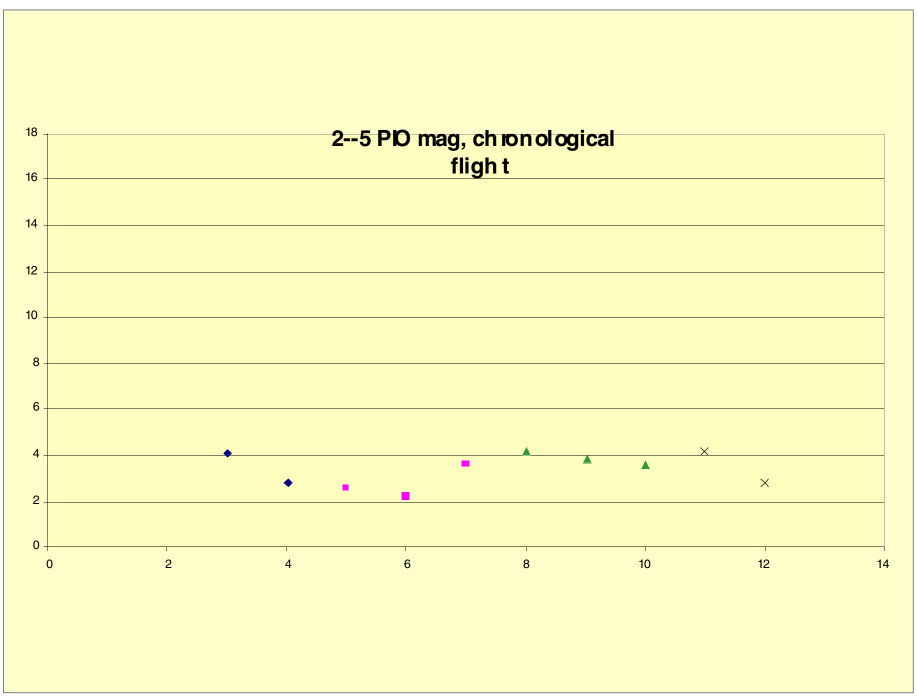


SOS Simulator, 2DU 20 deg/sec rate limit
20
15
10
5
0
-5
-10
-15
-20
10
20
30
40
50
60
70
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
q
Fes



5--10 flight PIO magnitude, chronological
18
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14


5--10 PIO
magnitude, MS-1
pilot A
pilot B
pilot C
pilot D
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30


2--5 PIO mag, chronological
flight
18
16
14
12
10
8
6
4
2
0
0
2
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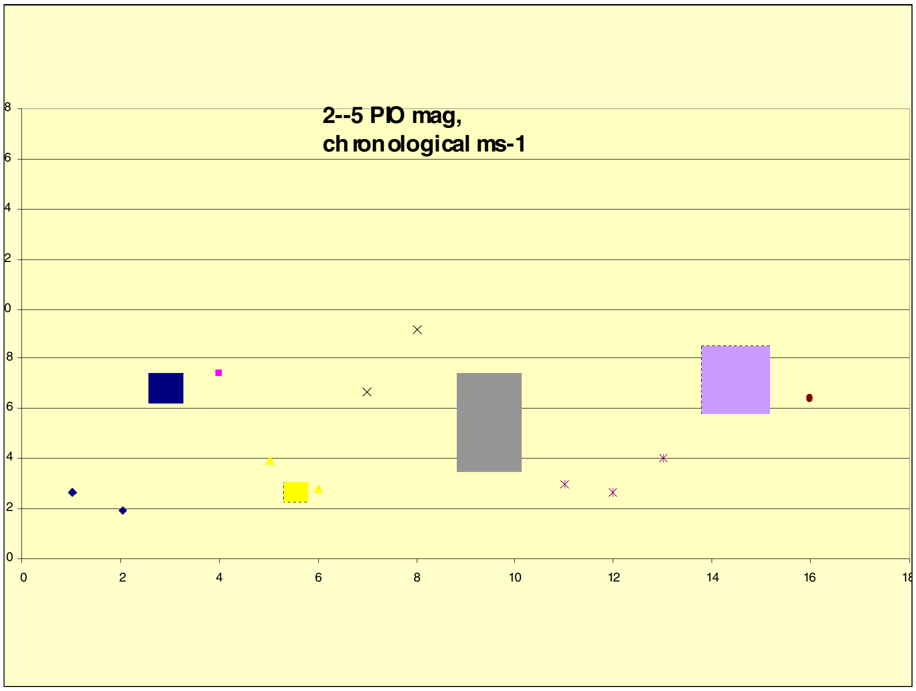
6
8
10
12
14



OTHER OBSERVATIONS

- INFLUENCE OF PREVIOUS RUN
- INFLUENCE OF KNOWLEDGE THAT TEST IS FOR PIO

PIO TRIGGERS

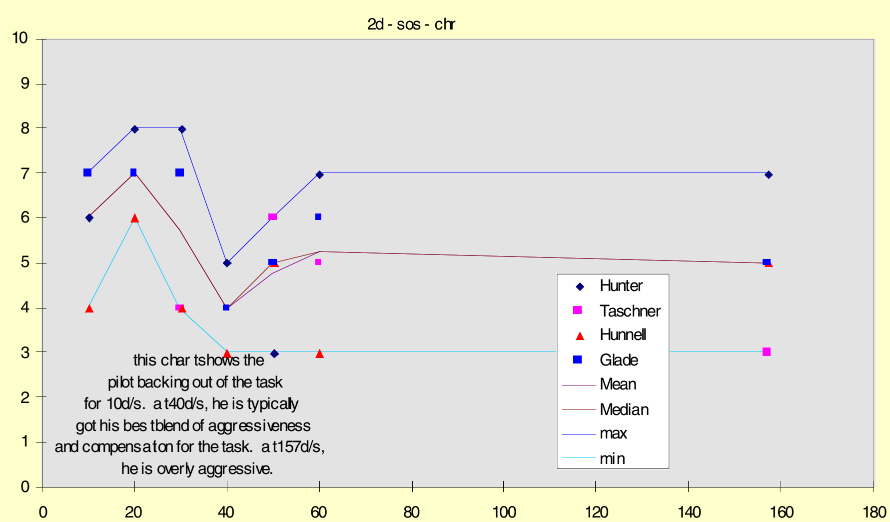
- FLIGHT: NOMINAL TASK PROVIDES TRIGGER
- SIMULATION: ARTIFICIAL STIMULUS MAY BE REQUIRED

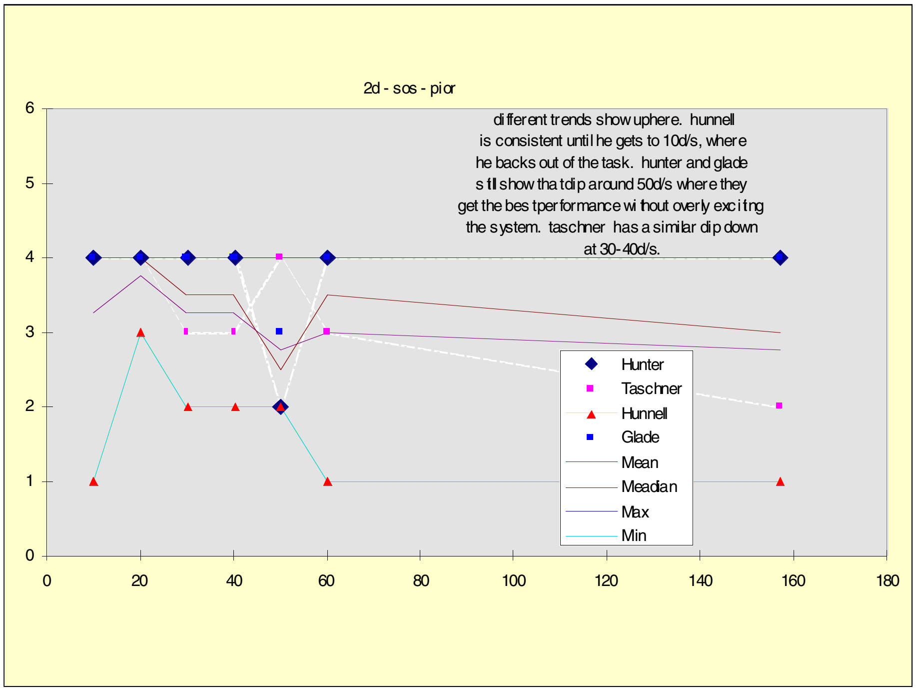
SUMMARY

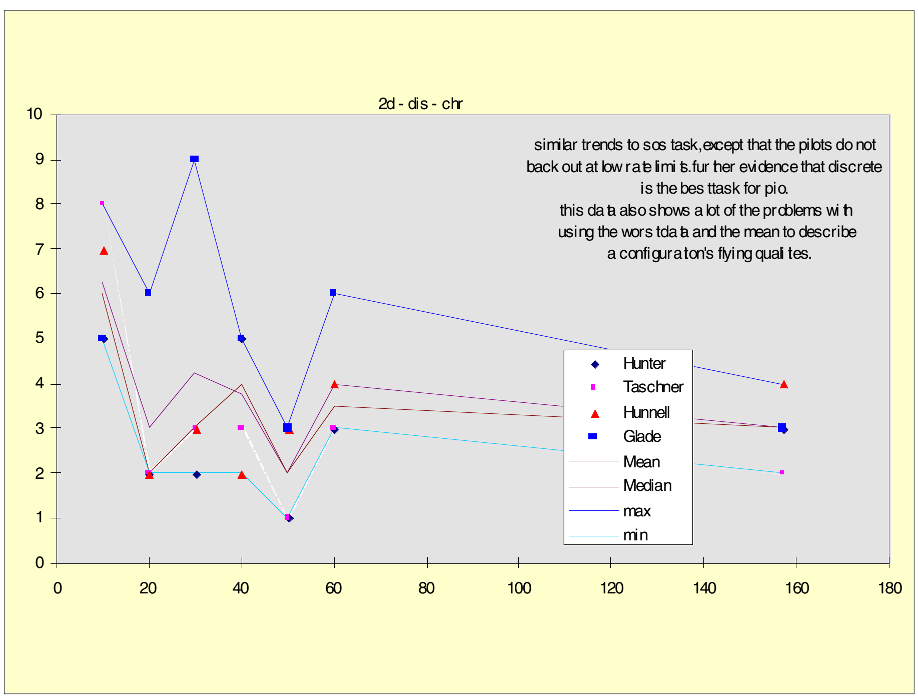
- **EFFECT OF MOTION** - MINIMUM CHANGE IN RATINGS, NOTICEABLE IN PHYSICAL CHARACTERISTICS
- **SAFETY PILOT** - ENDS TASK SOONER, MAY AFFECT MAGNITUDE
- **EVALUATION TASK** - KNOWLEDGE OF PIO TEST MAY INFLUENCE RESULTS, ARTIFICIAL TRIGGER SHOULD BE CONSIDERED.
- **PIO FREQUENCY** - A RANGE NOT A NUMBER

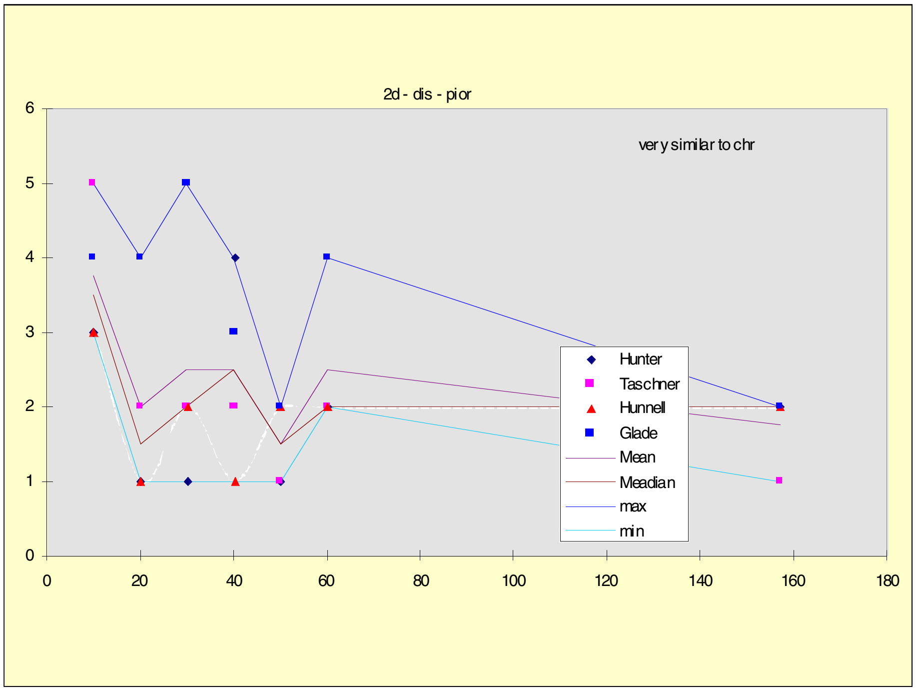
FLYING QUALITIES GROUP

- ~1952 Air Force Control Laboratory
- ~1962 Air Force Flight Dynamics Lab
- 1979 Air Force Wright Aeronautical Laboratory
- 1989 Wright Research and Development Center
- 1991 Wright Laboratory
- 1998 Air Force Research Laboratory
- 1999 deceased (no FQ research office)




2d - sos - pior
different trends show up here. hunnell
is consistent until he gets to 10d/s, where
he backs out of the task. hunter and glade
still show that dip around 50d/s where they
get the best performance without overly exciting
the system. taschner has a similar dip down
at 30-40d/s.
Hunter
Taschner
Hunnell
Glade
Mean
Meadian
Max
Min
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
160
180


2d - dis - chr
similar trends to sos task, except that the pilots do not
back out at low rate limits. further evidence that discrete
is the best task for pio.
this data also shows a lot of the problems with
using the worst data and the mean to describe
a configuration's flying qualities.
Hunter
Taschner
Hunnell
Glade
Mean
Median
max
min
10
9
8
7
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
160
180


2d - dis - pior
very similar to chr
Hunter
Taschner
Hunnell
Glade
Mean
Meadian
max
min
0
1
2
3
4
5
6
0
20
40
60
80
100
120
140
160
180

PHANTOM WORKS

Stability, Control & Flying Qualities

A Summary of the Ground Simulation Comparison Study (GSCS) For Transport Aircraft

PIO Workshop at NASA-Dryden
April 6-8, 1999

Terry von Klein
Stability, Control, & Flying Qualities Group
Boeing – Phantom Works, Long Beach

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Stability, Control & Flying Qualities

GSCS Goals

- Fly a Test Transport Aircraft
  - Degraded FCS Configurations
  - Evaluate Pilot Induced Oscillation (PIO) Characteristics
- Evaluate Identical Configurations in Simulation
  - PIO Characteristics
  - Motion & Fixed-Base Ground Simulation
- Compare Flight Vs. Simulation

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Test Facilities

- **Modern, High Wing Transport Test Vehicle**
  - Specialized, One-of-a-Kind Test Aircraft
  - Fly-By-Wire Flight Control System
  - Change-A-Gain (CAG) System

- **Motion-Base Simulator**
  - Tuned to Test Vehicle
  - Validated Math Models

BOEING

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FCS Configurations

FLIGHT CONDITION	FCS CONFIGURATIONS	HANDLING QUALITIES EFFECTS
High Speed Cruise Condition	Pitch Phase Lag	Add Up to 100 msec of Extra Time Delay in Pitch Response
(285 KIAS, Clean Wing, 25000 ft.)	Pitch Command Sensitivity	Increase Pitch Response to Pilot Input By a Factor of 2.0
Low Speed	Pitch Phase Lag	Add Up to 100 msec of Extra Time Delay in Pitch Response
Power Approach Condition	Pitch Command Sensitivity	Increase Pitch Response to Pilot Input By a Factor of 2.0
(145 KIAS, 12000 ft, Flaps & Gear Down)	Roll Command Sensitivity	Increase Roll Response to Pilot Inpu tBy a Factor of 2.2

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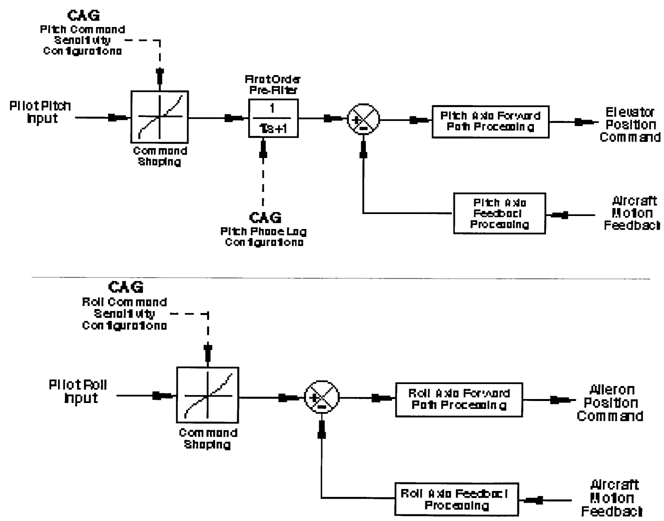
Stability, Control & Flying Qualities

Pitch/Roll CAG Locations



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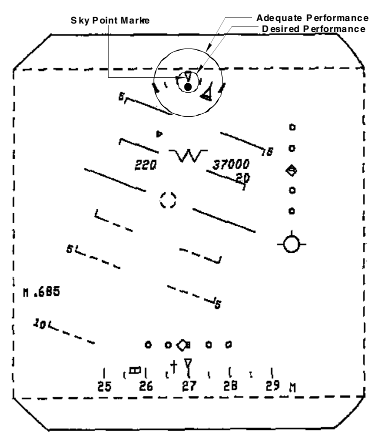
High Speed Evaluation Task

- **Boom Tracking Behind Tanker Aircraft**
- **Separation Distance of Approximately 1 Plane Length**
- **Pre-Defined Scripts of Boom Movement**
- **Feet on the Floor**



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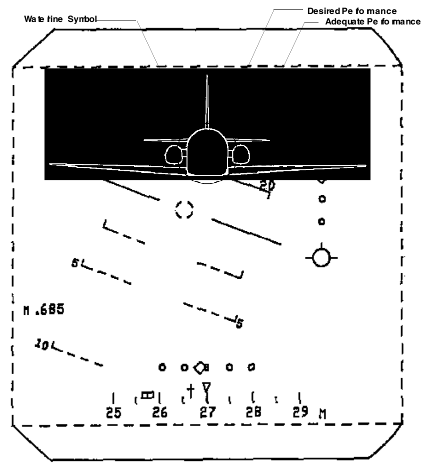
Low Speed Evaluation Task

- Formation Trail Task Following a Small Leader Aircraft
- Separation Distance of Approximately 2 Plane Lengths
- Pre-Defined Scripts of Leader Maneuvers
- Occasional Pedal Usage



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Testing Summary

- Flight Test
  - Two Evaluation Pilots
  - One Flight of 5.5 Hours Duration
  - Very Few PIOs Noted
  - Formation Trail Task Higher Workload Than Boom Tracking
  - Potential for Structural Mode Excitation
- Simulator
  - Minimum of Three Evaluation Pilots
  - Motion Response
    - Valuable at High Speed Test Points
    - Of Neutral Value at Low Speed Test Points
  - Structural Modes Not Modeled

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GSCS Status

- Very Early in Data Analysis Phase
- Complete Set of Flight Test Data
- Similar Results in Fighter Studies
- Variable Stability Capability of Test Vehicle
  - Respect Flight Safety

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General Flt. Vs. Sim. Results

- Simulator Harder to Fly
  - Control of Separation Distance
  - Differing Piloting Techniques
  - Simulator Generally More PIO-Prone
- Level of Target Aggressiveness
  - More Aggressive Target Required in Flight
- Pilot Ratings
  - Inconsistent Pilot Rating Trends in Simulator
  - More Consistent Pilot Ratings in Flight
- Coupling Between Pitch and Roll Axes
  - Degraded Axis Led to Perceived Change in Off-Axis
- Low Speed Motion Cueing

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Discrepancy Factors

- Simulator Transport Delays
  - Visual, Displays of Sensor Information, Motion
- Reduced Simulator Cueing Environment
  - Level of Visual Detail
  - Depth Perception
  - Visual System Field-of-View
  - Visual System Alignment to Fuselage
  - Motion Responses
    - Travel Limitations
- Differing Pilot Input Spectra
  - Pilot Adapting to the Situation
  - Structural Mode Impact

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GSCS Background

- Sponsored By AFRL/USAF
  - Technical Monitors: Wayne Thor & Dave Leggett
- Flight Test Planning
  - August 1996 - March 1997
- Simulator Evaluation & Analysis
  - April 1997 - August 1997
- Flight Testing
  - August 1998
- Data Analysis
  - Ongoing

BOEING


Real Experiences
In The Frequency Domain
Randall E. Bailey
and
Andrew R. Markofski
VERIDIAN
Veridian Engineering
Intelligent Information Solutions for Global Security & Safety
Veda
Pacific-Sierra Research
Veda Systems
Systems Research Laboratories (SRL)
RAIL
Calspan

Outline

"Real (and Imaginary) Experiences in the Frequency Domain"

- **Background**
  - **Purpose of Briefing**
- **Frequency Domain Analysis 'Fundamentals'**
- **Real Data Analysis**
  - **Realistic Assumptions?**
- **Concluding Remarks**

VERIDIAN

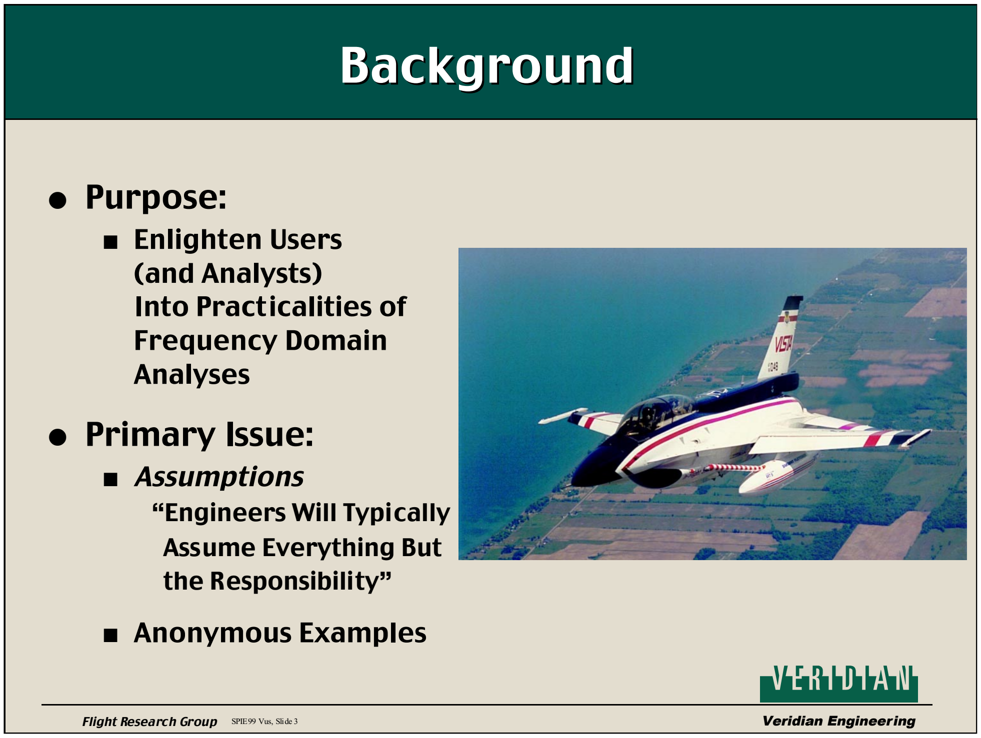
Flight Research Group SPIE99 Vus, Slide 2 *Veridian Engineering*

• Not intending to be too "Complex" with this presentation on frequency response analyses - therefore, the presentation title is only "Real Experiences in Frequency Domain" as opposed to "Real and Imaginary Experiences in Frequency Domain." Pun intended.

• This is the outline of talk.

• What is meant by "Real Data" is experiences where the assumptions needed for frequency domain analysis are implicit -- unspoken, but may not be realistic or compatible with data from real airplanes.

• In many cases the ease of use of the tools themselves tempt an engineer to treat the analysis as a black box.



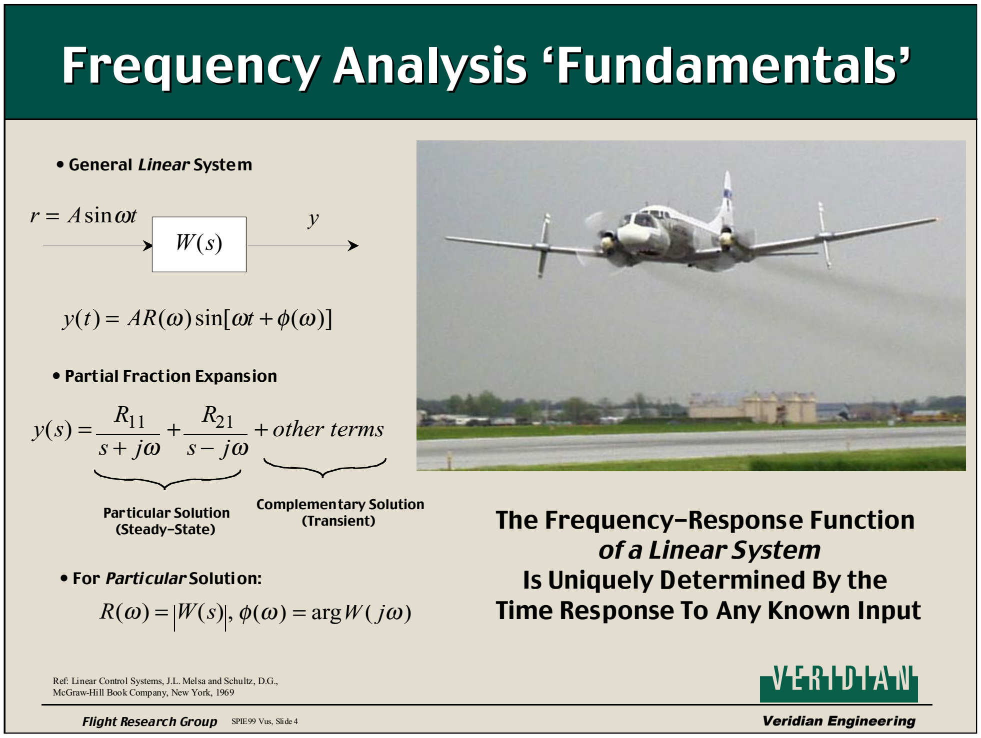
• So the purpose of this presentation is an attempt to enlighten the users and analysts involved in frequency domain based FQ/PIO criteria of the errors in their ways… To champion the cause of common sense over common practice.

• The problem is NOT necessarily the criteria or using the frequency domain - the problem is that the analyses for nonlinear/real aircraft data are not trival nor are they "independent" of assumptions. The criteria are not explicitly considering these assumptions and the users are not aware of the assumptions.

• Engineers are infamous for "assuming" everything but the responsibility. Assumptions are always used. Keep knowledge of them and use engineering judgment for applying techniques wisely.

• Maybe not such a good idea to bash engineers in front of a roomful of engineers. Probably would have gone over better at SETP or at a board meeting. Hmmm….

• Anonymous examples are used in this presentation to highlight "assumptions" - The examples are of using tools, applying these criteria and concepts rigidly. The definitions in many cases need revision and clarification. Assumptions may be incorporated in the criteria, or distributed to the user, or understood by the user/analyst. Wrong answers are being found.



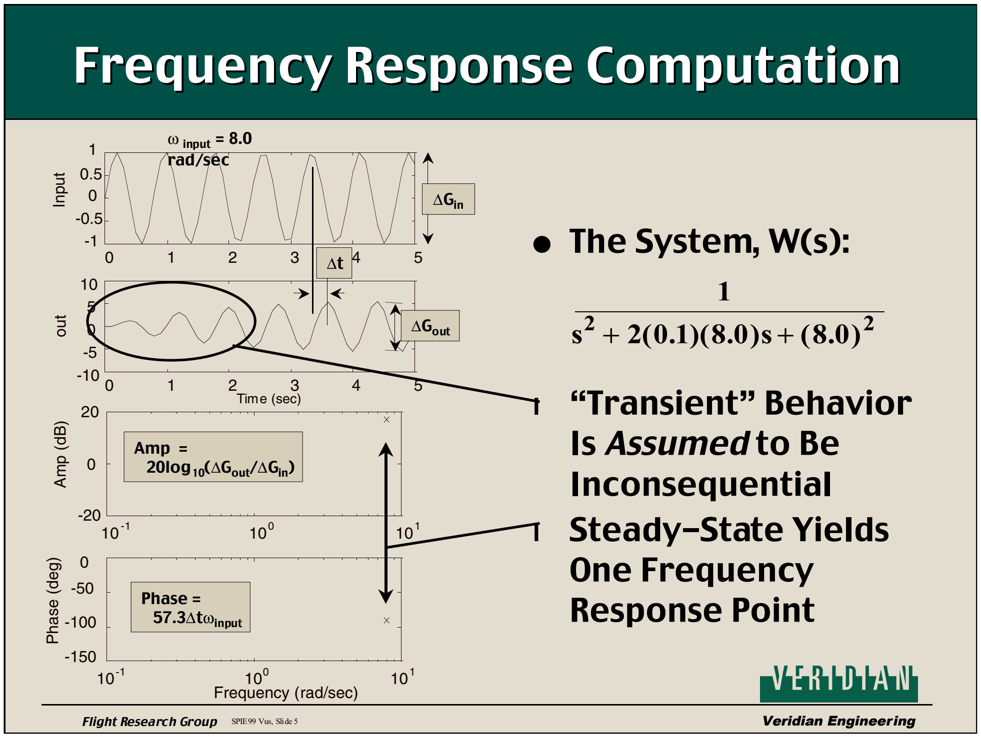
• Emphasis on FUNdamentals… The fundamentals of freq. domain analysis are that the response (y(t)) out of an arbitrary system (W) in response to an input, r, can be decomposed by partial fraction expansion into essentially three terms using Laplacian operators.

• The first two terms are the "particular" solution. The remaining terms are the "complementary" solution.

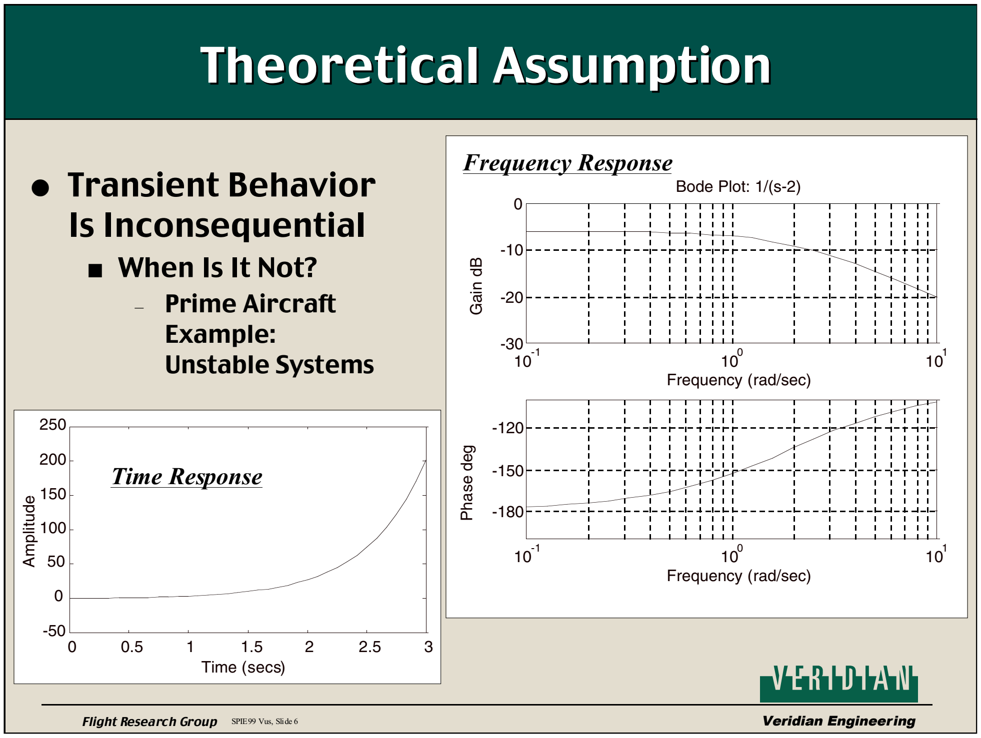
• The "particular" solution is the "steady-state" contribution of the response, y. The time response, y, is thus described from the frequency response of black box (or transfer function) where R= magnitude and ϕ = phase of W.

• The key to this fundamental property and why Frequency domain analysis is so nice for engineering use, is that "The frequency response function of a *linear* system is *uniquely* determined by the time response to any known input."

• The key priniciples/assumptions to remember from this are: "LINEAR" and "Ignoring the Other Terms"



- An example of these principles is shown.
- Transfer function of system, W, is as shown.
- Input is 8.0 rad/sec sine wave.
- After transient behavior (assumed to be inconsequential), steady-state can be used to find phase and gain (freq. response) at the input excitation frequency.
- The opposite principle also works (freq. domain to time domain) since we are analyzing a LINEAR SYSTEM.



- THEORETICAL = do not apply to REAL WORLD

First example of a BAD ASSUMPTION.

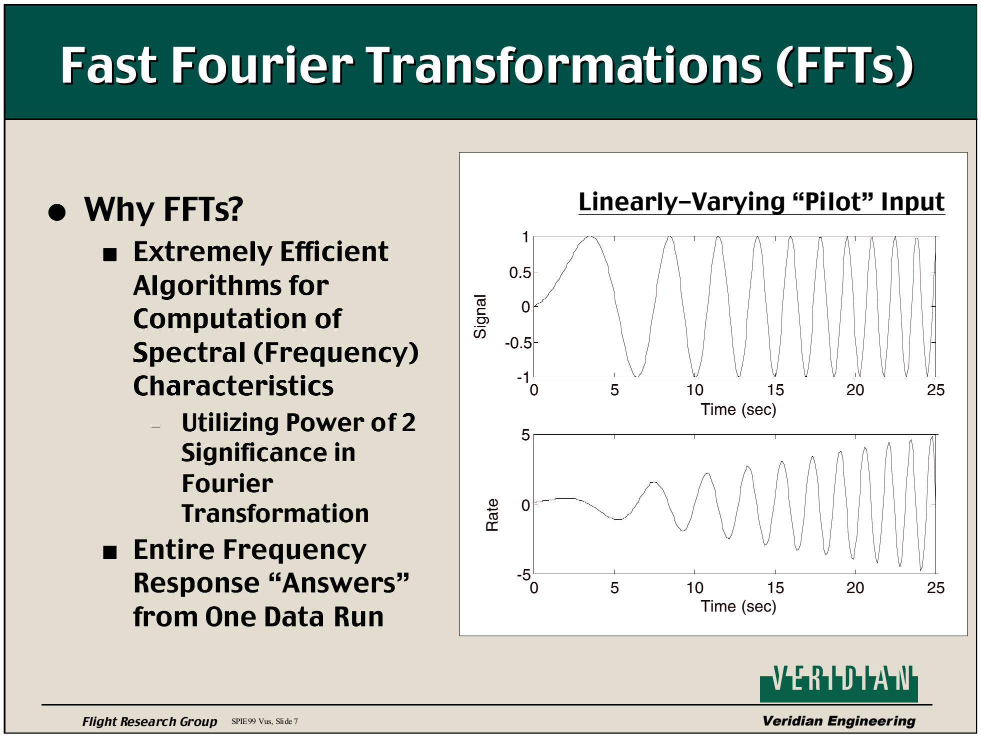
- Ignoring "transient behavior"

For example, the best example of when this is a problem is for an unstable system.

Unstable systems have frequency responses. The uniqueness properties between time and frequency domain still apply.

The problem is that it is **impractical** for this identification in the real-world. From the time response, the transient behavior "overwhelms" the time response and the "steady-state" frequency response characteristic is "hidden" in all practical sense of the word.

This point will be returned to at a later point in presentation.

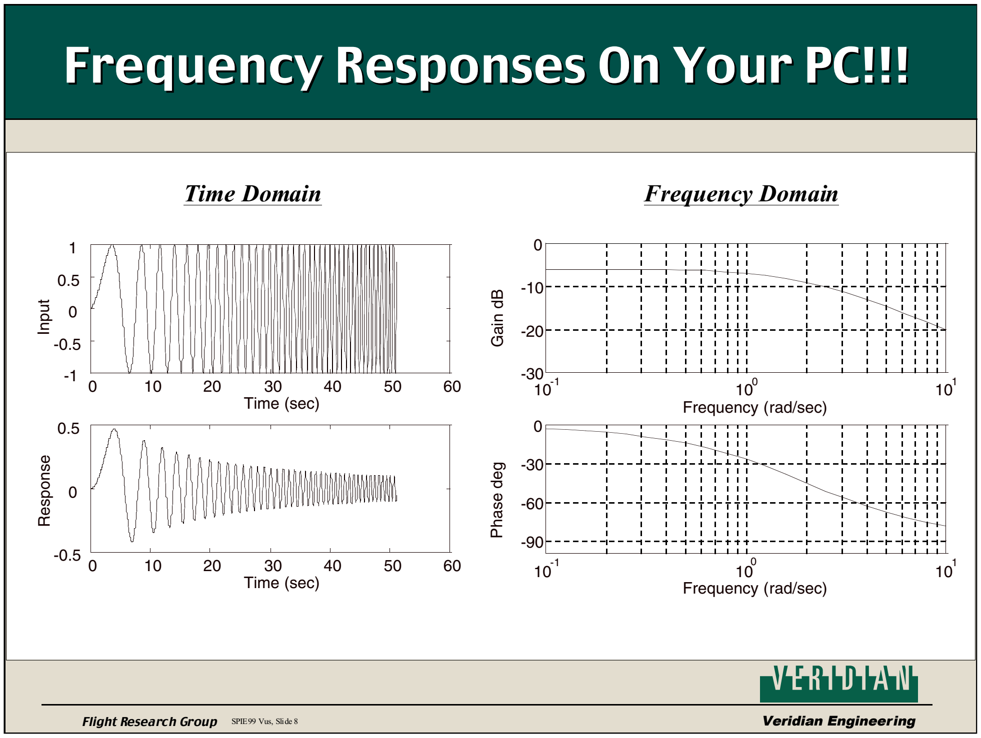


• Most practical method for frequency response computation occurs from Fast Fourier Transformations.

• Extremely efficient algorithm for transformation to frequency domain. Utilizes power of 2 in time history sample.

• "Entire" answers from one time history.

• Involve a whole set of their own ASSUMPTIONS



• Example of time response and frequency response.

• Example showing a "linearly varying" frequency input.

• Note that this is for a linear system.

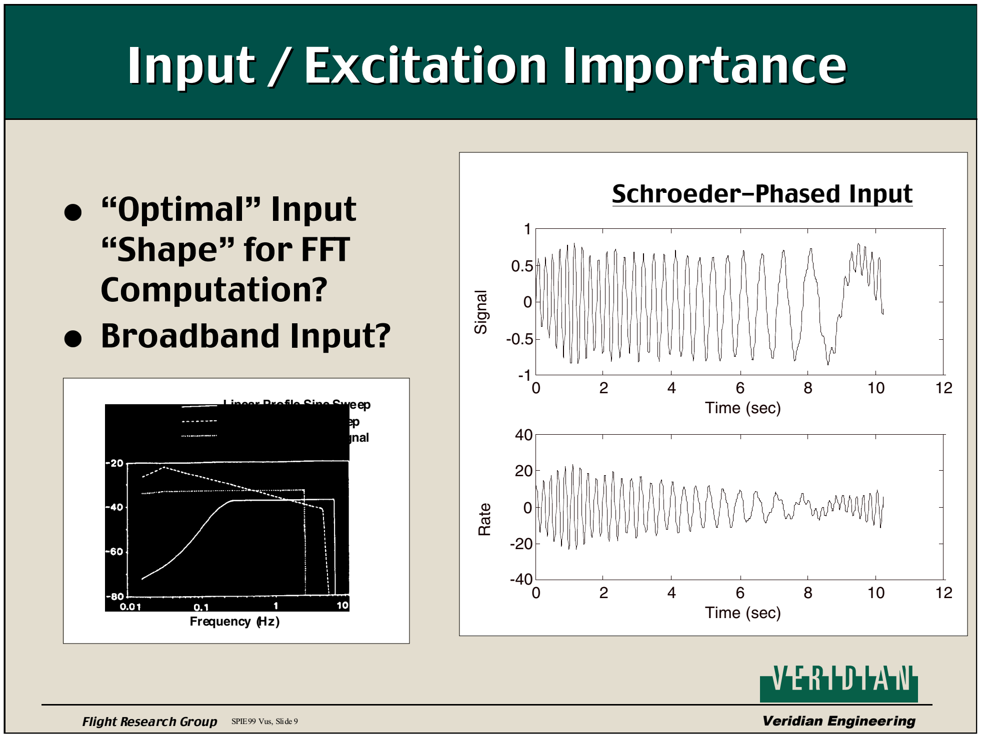
• Everyone can do them. No pain, no suffering.

• Tools make it easy to apply FFT without looking at the whole picture.

• Of course, now that everyone can do them. Everyone does. Do they all know the "underlying assumptions" involved in this transformation?

•"Garbage In, Garbage Out"?

• "A Little Knowledge is a Dangerous Thing"?

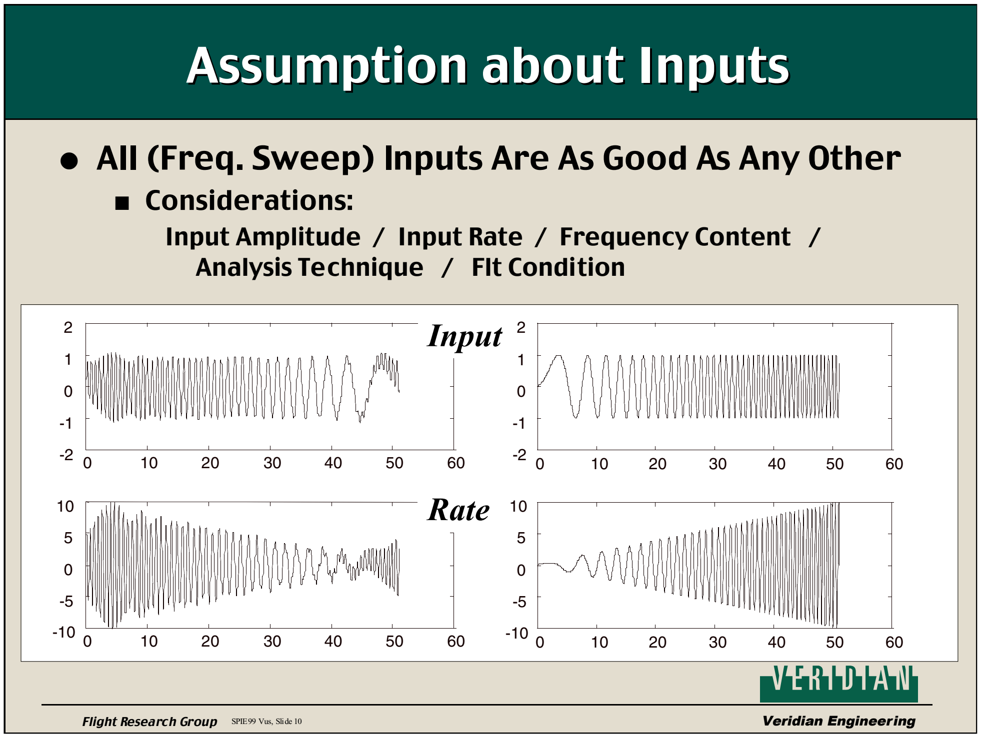


• A practical matter, not considered by many, is the importance of the input excitation.

• Unlike the "frequency sweep" input, it is not the "optimal/ideal" input

• Schroeder-phased inputs are better. Chirp-z inputs are also better.

• We will visit the importance of input on the next chart.



• Another bad assumption illustrated concerning inputs.

• In practical terms, the input for the frequency sweep has to consider: the amplitude, amplitude rate, frequency content, analysis technique that will be used, and flight condition.

• Again, for Single-input, single-output, no noise, linear, time-invariant system analysis, all of these items are immaterial (with exception of frequency content). This is NOT the real-world.

  • Input amplitude: important for signal-to-noise ratio.

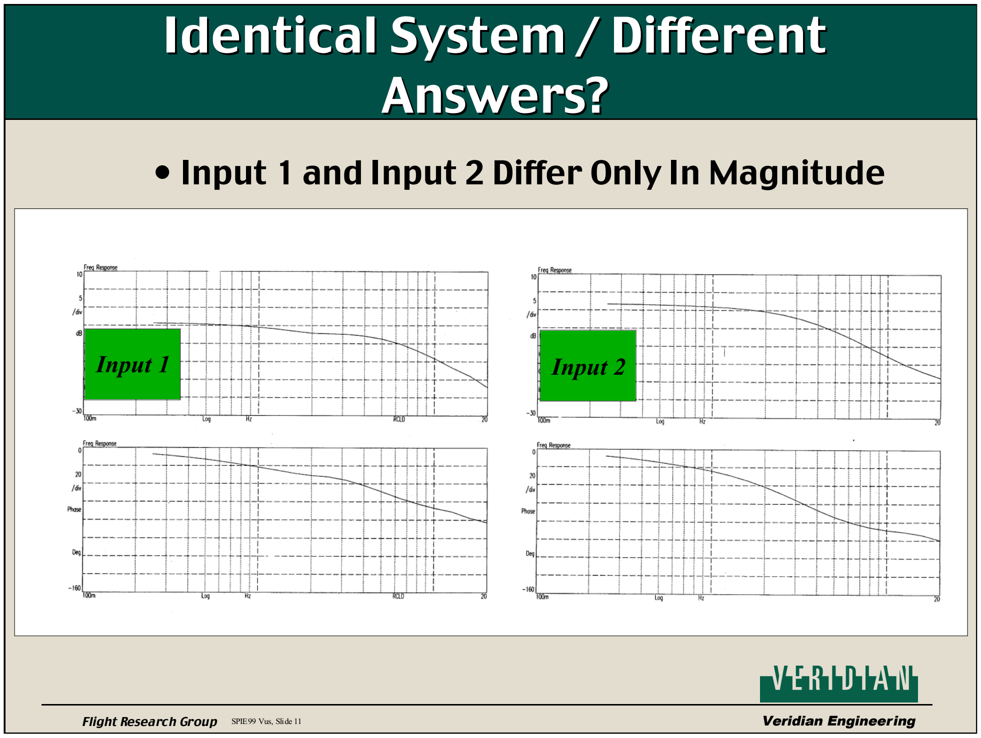
  • Input rate: important for "rate-limiting effects"

  • Freq. content - determines range of "valid" data

  • Analysis technique - ensembling of windowed data usually requires "broadband" / noise-type excitation across entire time history. Schroeder-phased inputs are tuned to frequency FFT harmonic frequencies (for lack of a better word).

• MORE DATA = Better??? Only for certain circumstances

• Flight Condition - Tradeoff between "constant" flight condition and accurate low frequency identification. Phugoid issues in particular. Low frequency inputs will excite phugoid (i.e., speed changes) - these are "real" effects yet can be "different" than what some people want (i.e., constant speed approx. for instance). Have to be careful what you asked for...



• An example of input importance.

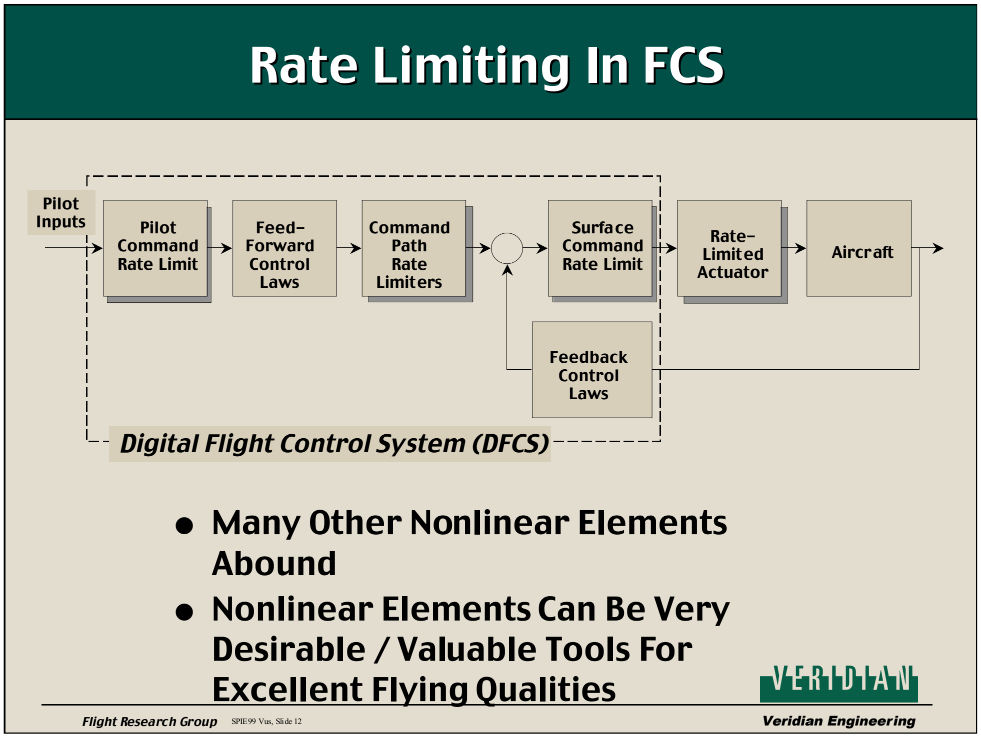
• System under identification is identical.

• Comparison of two frequency responses generated using two different sized inputs.

• Very, very different results depending upon input size.

• System was nonlinear.

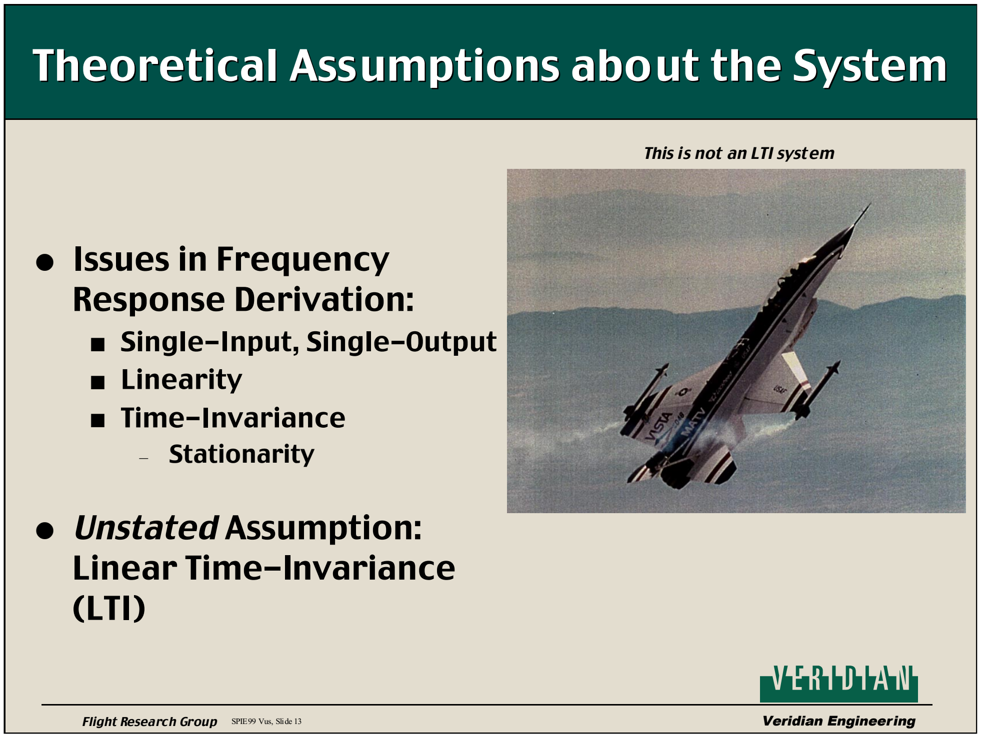
• Analyst said - “what’s going on. You asked for frequency responses and I got different “answers” every time.”



• A schematic diagram of "typical" rate limiter locations. Many other "nonlinearities" abound - not shown.

• Some limiters are intentional and necessary (ie., the surface command limiter) - others are physical limitations (i.e., the actuator)- some are used "erroneously" (such as the pilot command rate limiter) because HQDT "requires" it. (For instance, if max. value, unrealistic inputs are used just for "PIO" evaluation, an easy solution for the designer is to slap a "pilot command rate limiter" in the forward path. The result is that a "PIO" will not happen for the unrealistic HQDT task. However, the real result is that 20-25 msec of time delay is now added to the flight control system and the potential for a real PIO is increased just because some people teach the wrong thing for HQDT.)

• Nonlinearities are not bad. In fact, they are quite the opposite. They are necessary for good FQ. The only problem is making sure that the FQ tools can identify these "good" qualities and not legislate against them.



- THEORETICAL basis = do not apply to REAL WORLD
- The assumptions in freq. response derivations are:

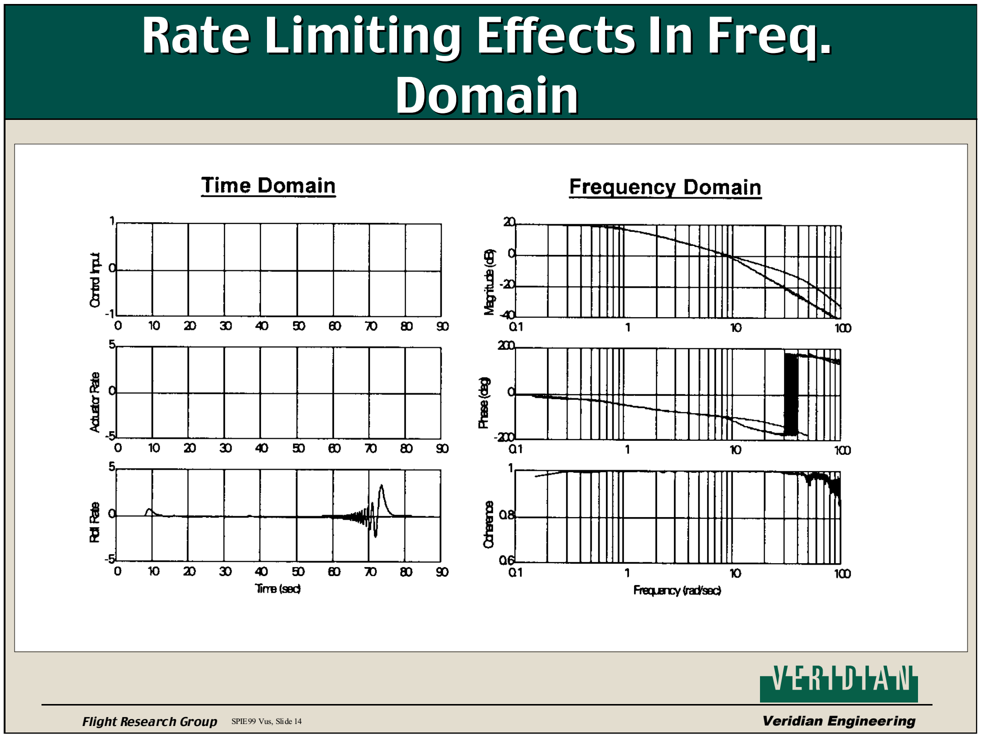
• (Many times, but not necessarily) Single-input, single-output (I.e., output is caused only by the one input)

• (Always) Linearity (ie., linear system is $q=M_{\alpha}\alpha+...$, nonlinear system is $q=M_{\alpha 2}\alpha^2$ etc.)

• (Always) Time-invariance (ie., y = function of time) (Stationarity is the "controls engineers" term for time invariance)

• Linearity conditions are easily violated by changes in flight condition, position and rate limits, breakout force, friction, hysteresis, nonlinear command gradients, etc…

• Time variation is also a rate limiting effect. In other words, the FFT analysis is assuming that over the time period for the identification, that the system has not changed.



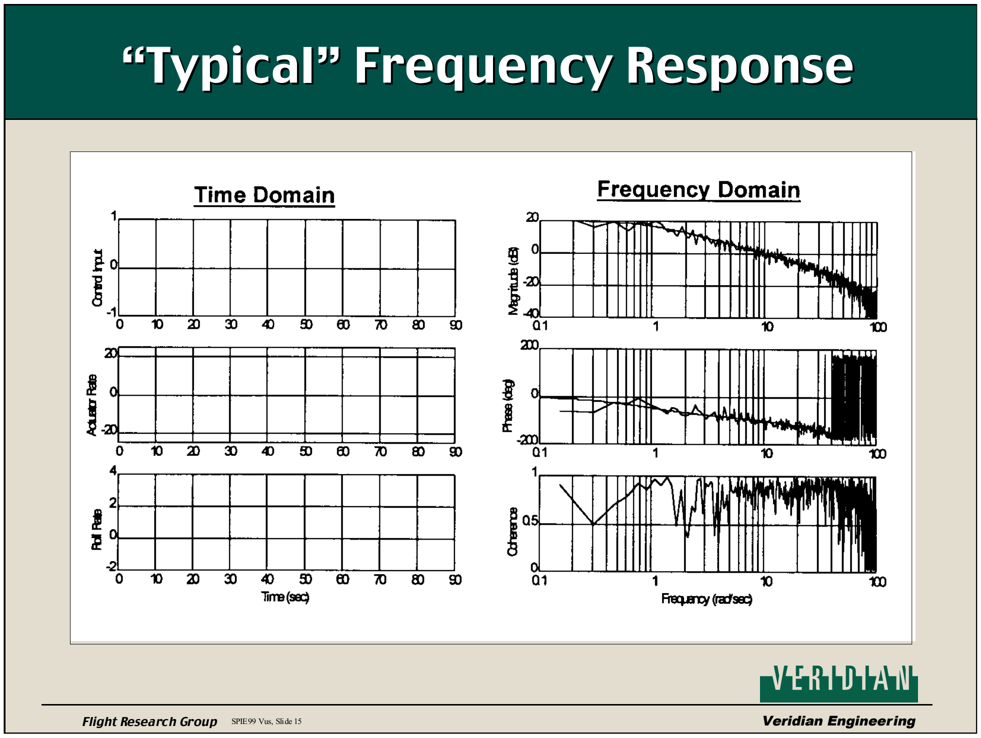
• Can rate limiting affects be identified in Freq. Domain? Yes. Here's an example.

• Note phase rolloff and amplitude attenuation.

• However, the most important condition for this result is that the rate limiter is no longer "time varying" - it's a quasi-steady. See rate signal above.

• HOWEVER, hard part - for this to occur, amplitude and frequency of the input to the rate limiter element depend on lots and lots of factors *in real situations that cannot* typically be predicted or repeatable from run-to-run, pilot-to-pilot, etc.

• Particularly for rate limiters that are "buried" in a control law - that is, the inputs depend not only on the pilot inputs but also on the feedbacks, etc. A prime example is the actuator command rate limiter shown on a previous slide.



• Here’s a more “typical” example. Note variation in rate limit. Also, noise is added to input and output. (Not a laboratory condition!!)

• Introduce “<u>coherence</u> function” at this point.

Purpose: Evaluation of “goodness” of FFT.

Real name: “Ordinary” coherence function for SISO case.

• Coherence lets analyst know if FFT/freq. resp. is “valid”

• Not valid (ie., coherence values go <1) if:

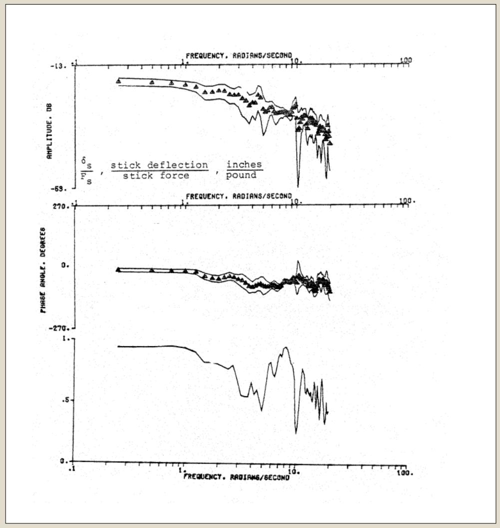
1) Extraneous **NOISE** is present in the measurements

2) System relating x and y (input and output) are <u>not linear</u>

3) Output is due to input as well as other inputs -- not SISO

"Accepting" Error in Identification

- **Ignore Significance of Coherence**
  - "Ordinary" Coherence <1.0
    - Noise
    - Nonlinearities
    - Not SISO
- **Coherence "Significance" Has Been "Lost"**
  - System Identification From Tracking (SIFT)
    - AFFTC-TR-77-27, Nov. 1977, Twisdale & Ashurst
  - Must Re-Establish Its Role



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Veridian Engineering

Flight Research Group

• Reiterate: Ordinary Coherence < 1 - Noise, Nonlinearity, Not Single-Input, Single Output (ie., multiple inputs, turbulence, etc can cause violation of SISO)

• Can't just "ignore" coherence - have to understand why coherence does equal 1.0. Involves more analysis of the input and output, and tracking the error.

• Coherence has been used as a "discrete" ie., if coherence>0.6 data is "good" Not a good thing to do unless you make that level very stringent (coh>0.9, >0.95). Can be dangerous (Bad Assumption). Coherence is similar to correlation coefficient analogy. 1.0 correlation is "perfect." Correlation = 0.6, correlation to real data is *not* good. Many examples of coherence >0.6, <0.9 where data was "bad." (i.e., not what was expected. If left un-investigated, would have gotten wrong answer)

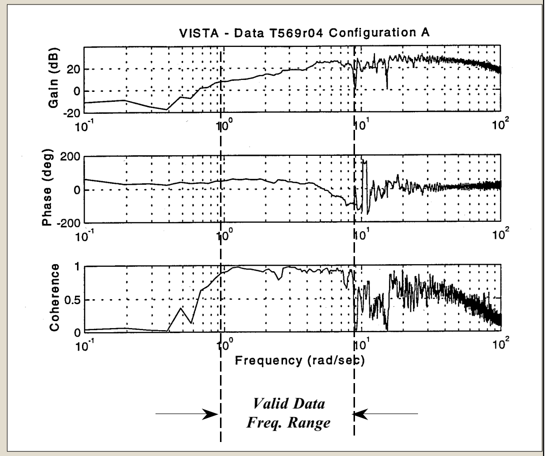
• More appropriately, coherence is *directly* relatable to error in frequency response estimate. This significance has been lost! (Twisdale did this 20 years ago!)

• Must get back to its signficance if frequency response analysis is going to do anything for us.

•Answers from criteria using this data will tend to be regions rather than points

Common Practice Assumption

- **Following "Established" Rules**
  - **Equivalent Systems: Typical Range for Match: 0.1 to 10–20 rad/sec**
    - **Ignoring Coherence, or**
    - **Using All Data Points, Thus, Distorting Weighting Functions, or**
    - **Identification / Inclusion of Low and/or High Frequency LOS Terms Beyond "Valid" Data**



VERIDIAN

Flight Research Group

Veridian Engineering

• We've had experience where - after "derivation" of a frequency response, the "rules" are blindly followed for such things as an equivalent system.

• Neglects phugoid, high order & nonlinear dynamics, structural dynamics, sensor dynamics, and recording filters. Assumes constant flight conditions.

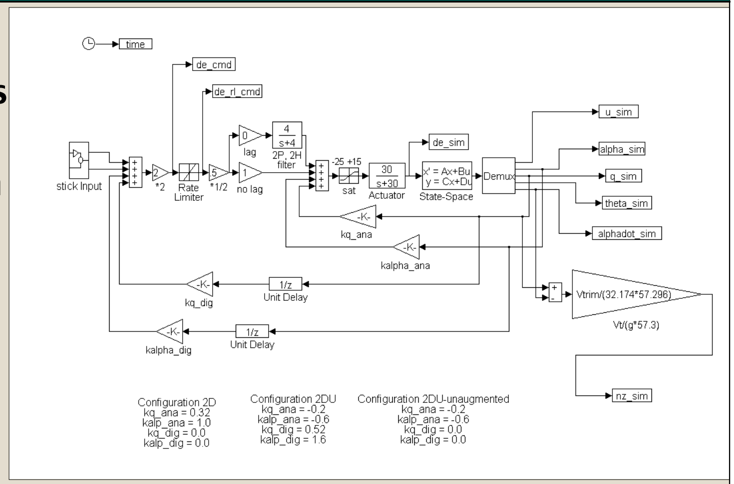
• Coherence has been ignored (see previous slide)

• Persons have used "all the data points" from a FFT for equivalent system derivation. This inappropriately weights the high frequency equivalent systems match at the expense of the low frequency due to the 1/dt frequency spacing of the data (more pts at high freq., fewer at low freq.)

• Although the freq. range of valid data was "narrow," extrapolation outside the range was allowed to get a "equivalent match." Unfortunately, answers can be MISLEADING.

HAVE LIMITS Example

Configurations



2D: stable with rate limit in command path only

2DU: unstable augmented to get 2D characteristics with rate limit in feedback

Flew with rate limits from 60 to 10 deg/sec

VERIDIAN

Flight Research Group SPIE99 Vus, Slide 18 **Veridian Engineering**

• This is a Simulink diagram used for the "Have Limits" flight test program.

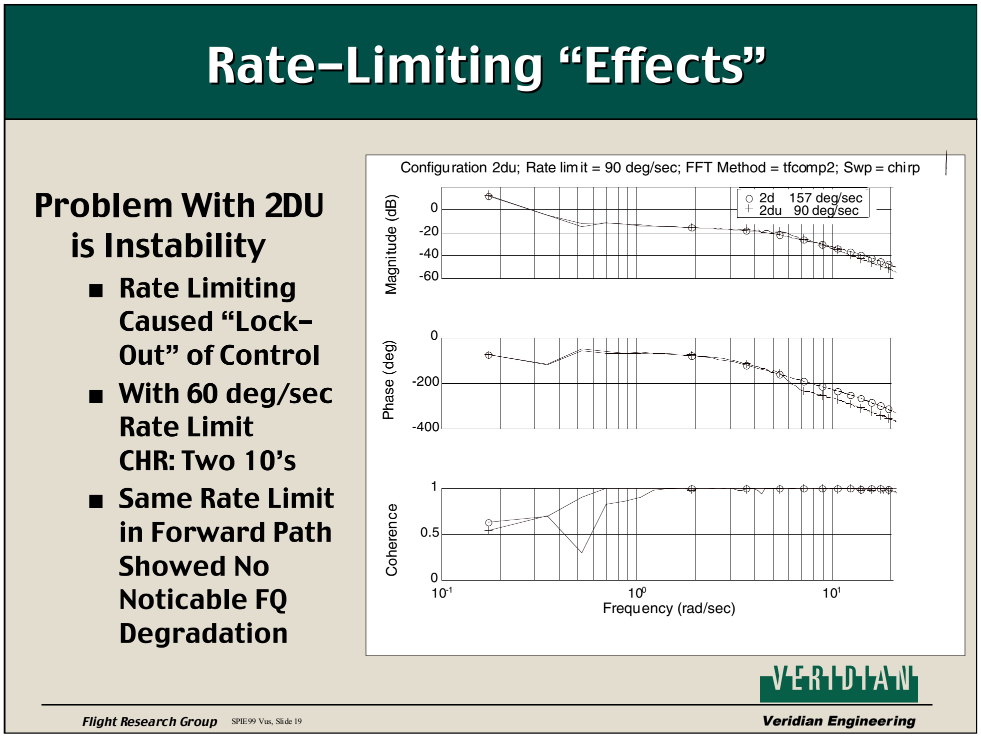
• This model was used to assist the engineers in visualizing the set-up of the experiment.

• Subsequent to the experiment, this model has been distributed to users to aid in analyzing the "Have Limits" data.

• Key "feature" in the data base, analysis, and set-up for the "Have Limits" flight test is Configurations 2D and 2DU.

• Config 2D has the rate limiter in the forward path only.

• Config 2DU was a simulated unstable airframe - using analog feedbacks, without rate limiting around the NT-33 Airframe - with an outer loop feedback structure to augment the simulated unstable airframe to match Config 2D dynamics. The key difference is that the rate limiting term includes the feedbacks for Config 2DU and an unstable airframe.



• In a very brief summary, a key conclusion from the Have Limits program is that Config 2DU have very poor flying qualities. Pilot Ratings were 10 for the least amount of finite rate limiting (ie., with 157 deg/sec rate limiting - essentially no rate limiting, 2DU got ratings of 2, 5, and 4. But for as little as 60 deg/sec rate limiting, two 10's were given.

• The FQ deficiency for Config 2DU was loss-of-control. Once the aircraft was on the rate limit, the feedbacks were locked-out and the aircraft entered a departure scenario. (NT-33 VSS was disengaged upon loss-of-control).

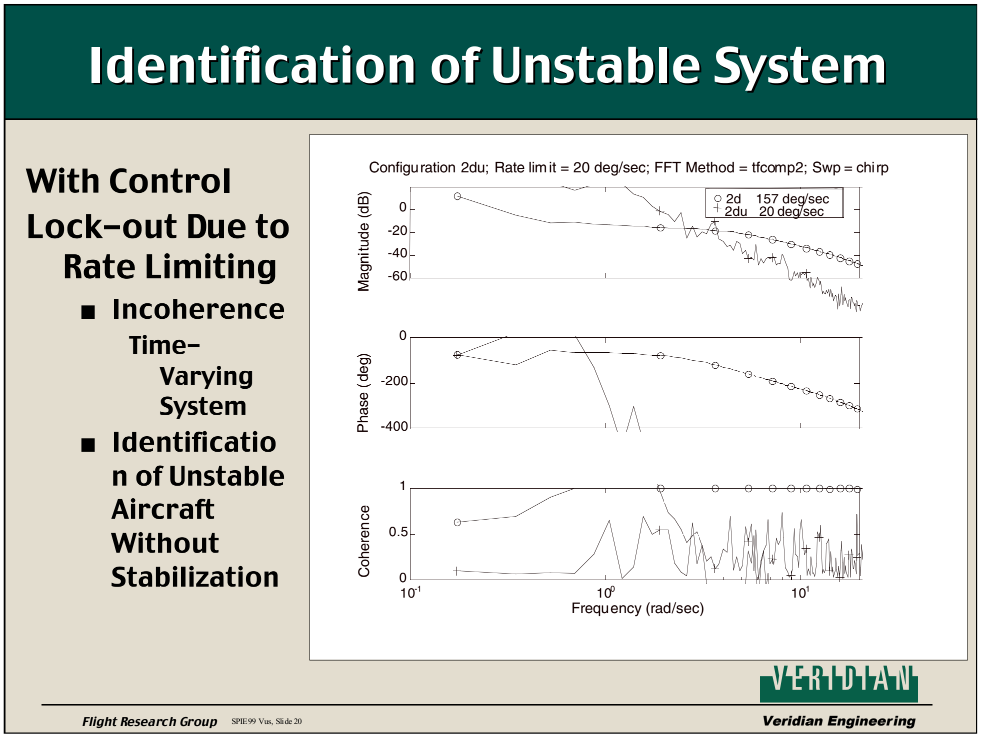
• Same rate limit, in forward path, was not a noticeable flying qualities influence.

• Using the Simulink model and assuming a pilot input size, "rate limiting" effect in frequency domain is noted.

• Issues:

1 - have to "assume" a pilot input size;

2 - can't get freq. domain "answers" for rate limit values < 90 deg/sec Only done analytically, not flown.



• As example, for 20 deg/sec rate limit, the frequency response data for 2DU is garbage. Reason: the aircraft hits a loss-of-control issue. Time varying system with nonlinearity. Also, once aircraft is in rate limiting, the feedback is "ignored" and the bare airframe characteristics are what is being identified.

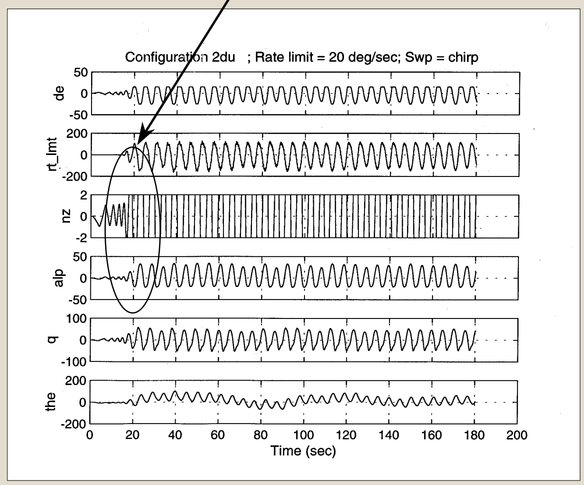
• The results are essentially not valid.

Transient Response Dominates

Time Response shows when the rate limit is encountered, 2DU reverts to unstable open loop system.

FFT-derived frequency response is not valid

Control Of Vehicle "Lost" – Departure



VERIDIAN

Flight Research Group SPIE99 Vus, Slide 21 **Veridian Engineering**

• Here the time history really shows what's going on. Specifically, like the earlier example, the transient response is NOT negligible.

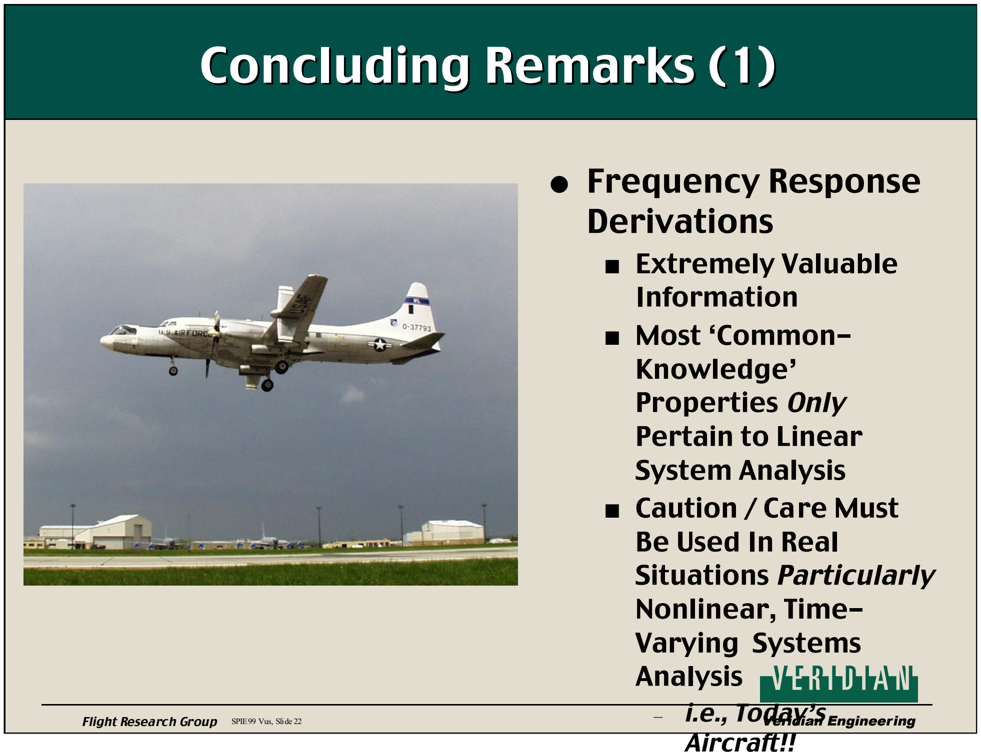
• Once aircraft is in rate limiting, the feedback is "ignored" and the simulated unstable bare airframe characteristics are driving the response

• Once the rate limiting starts with Config 2DU loss-of-control occurs. Note the time histories where alpha goes +/- 25 degrees and the g's go way beyond +/-2 g's. (The plot is artificially limited to +/- 2 g's)

• FFT-derived frequency response is not valid since it is no longer linear aerodynamics or time invariant.

• In fact the response immediately goes beyond the scope of the small perturbation model.

• These agree with the results experienced in the flight experiment.



• Said enough. Just summarizing the points...

• Don't let them kill the messenger, Andy.

• Reiterate that Freq. Domain analysis *IS* a powerful tool - very useful. However, it can't be used carelessly. Unfortunately, it is...

• I've cited some examples. Many, many more were available but I couldn't put them into a 30 min. presentation.

Concluding Remarks (2)

- **Tools & Techniques for Proper Analysis Are Available**
  - e.g., System Indentifcation From Tracking (SIFT)
- **Retain Engineering Judgment in Analyses**
- **Scrutinize Assumptions**
- **Develop 'Standards'**

Flight Research Group SPIE99 Vus, Slide 23 **Veridian Engineering**

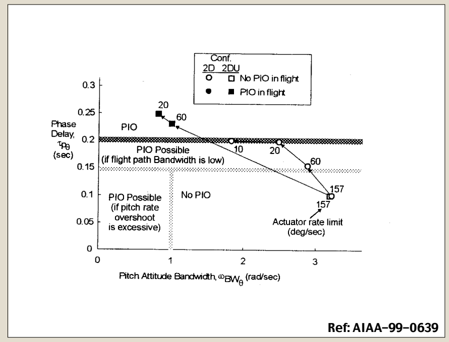
• Reiterate that tools are available or can be developed. Not rocket science.

• Clearly, evidence abounds that the fundamentals of frequency domain analysis are being ignored, forgotten, whatever - but things will get worse if they don't stop, step back, and think about what is being proposed and done.

• Standards for analysis will help.

Erroneous Rate Limiting Effect

- **Criterion Indicates "PIO" Problem**
  - **AIAA-99-0639 "Determining Bandwidth in the Presence of Nonlinearities"**
- **FQ Data Shows Loss-of-Control for Config 2DU**
  - **Correctly Predicts Pilot Rating for Wrong Reason?**



VERIDIAN

Flight Research Group SPIE99 Vus, Slide 24 **Veridian Engineering**

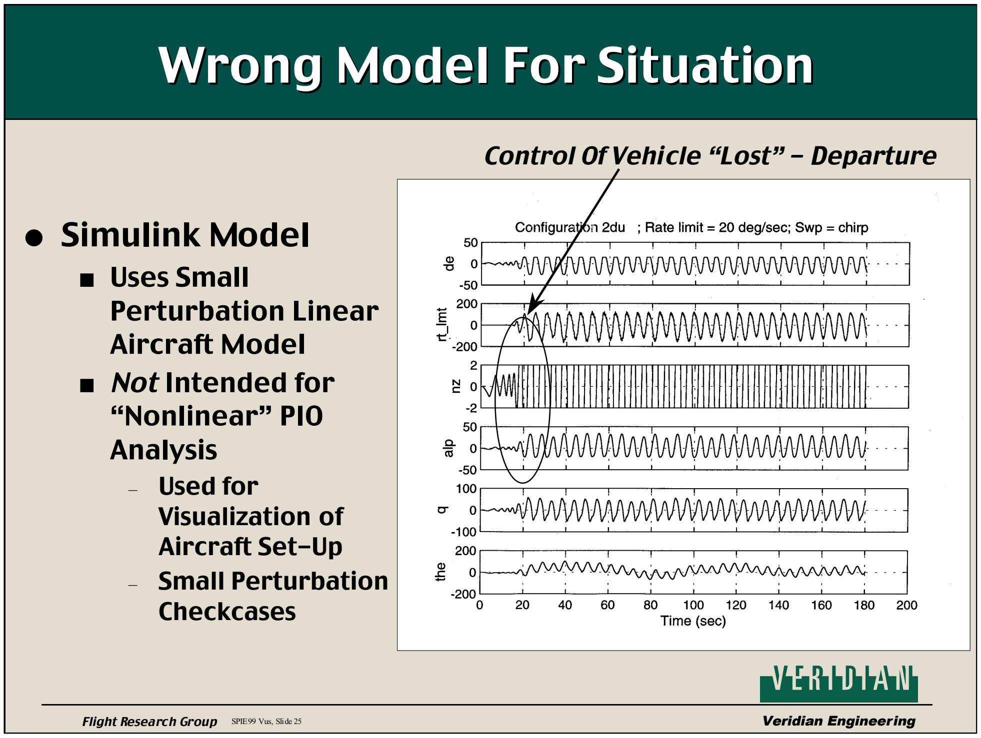
• In AIAA paper 99-0639, frequency domain data was presented for these cases.

• Don't know how these data were generated - can't repeat analysis.

• Further, they should show unstable aircraft behavior. They don't

• Finally, the frequency responses in 99-0639, show a feedforward, time delay effect of rate limiting - not the loss-of-control issue. That's what the bandwidth criteria, shown on the plot, indicate.

• Basically the criteria are predicting the right answer for the pilot rating, but for the wrong reason. The real data - the pilot comments - don't match the criteria. The criteria doesn't say "loss-of-control" for this configuration.



• Another problem with these analyses is the use of the Simulink model.

• The model was intended for visualization by Calspan and AFTPS engineers of the experiment. It was also used for small perturbation checkcases.

• The model uses a simple three degree-of-freedom, small perturbation math model of the NT-33.

• The scope of the validity of this model has NOT been determined. However, clearly, it is not valid once the rate limiting occurs with Config 2DU and loss-of-control occurs. Not the time histories where alpha goes +/- 25 degrees and the g's go way beyond +/-2 g's. (The plot is artificially limited to +/- 2 g's)

• Again, the model was never intended for the purposes that it may be being used for at this time. This should have been obvious from inspection of the "aircraft" model form.

Pilot Modeling for Resolving Opinion Rating Discrepancies

David B. Doman
Air Force Research Laboratory
April 8, 1999

Background

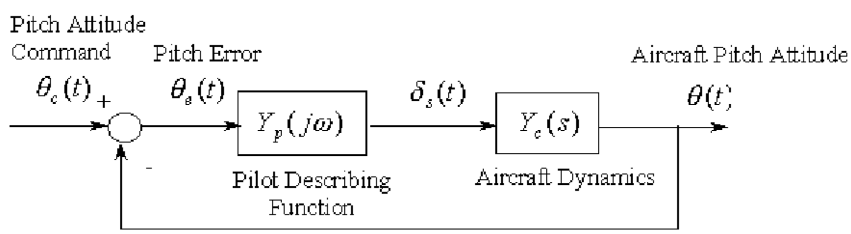
• Inter/Intra pilot opinion rating variability has confounded flying qualities engineers since the inception of the rating scales

•A method for extracting quantitative information from experimental data to provide insight into rating variability and help gauge the validity of ratings would result in a valuable engineering tool.

•**Idea #1** Extract metrics developed for pilot-in-the-loop flying qualities criteria from experimental frequency response data.

•**Idea #2** Estimate a range of ratings by using highly accurate models of pilots and varying physiological parameters over a reasonable set of values.

Pilot-in-the-Loop Pitch Tracking



Performance - Workload Criteria

Neal-Smith, Bacon-Schmidt, Efremov MAI:

•Closed-loop resonance

•Pilot phase compensation, (Pilot phase excluding neuromotor lag and time delay)

•Each assumed all pilots behave the same

Neuromotor lag (related to aggressiveness) and time delay vary over pilot population, What <u>range</u> of pilot ratings can be expected?

Optimal Control Pilot Models

Assumptions

• Compensatory Tracking (SOS)

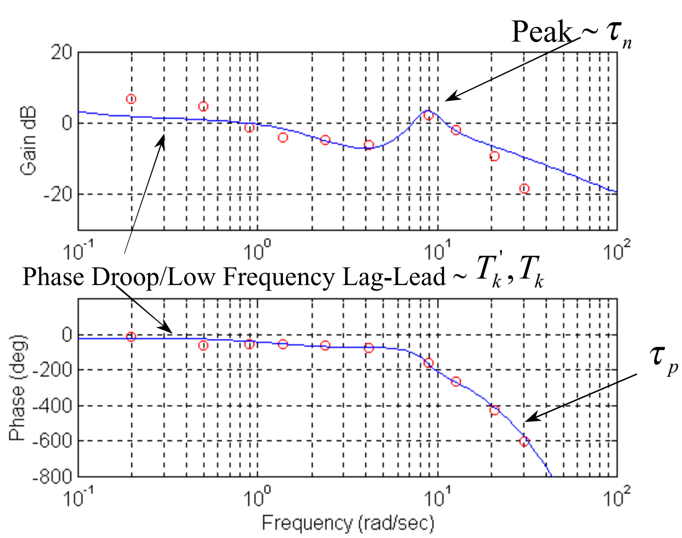
•Minimize mean squared frequency weighted tracking error subject to human operator limitations

$$J = E_{\infty}\left(e_f^2 + f\dot{u}_p^2\right)$$

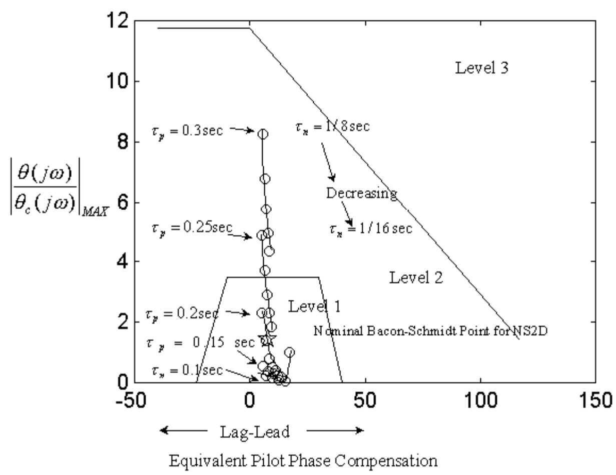
$$e_f(s) = \frac{T_k^{'}s+1}{T_k s+1}e(s)$$

Control rate weighting f directly linked to pilot's neuromotor dynamics.

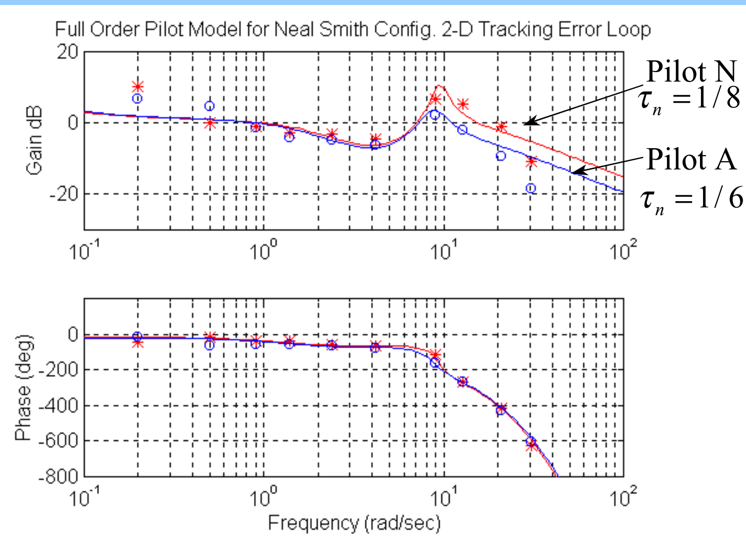
Fitting Describing Function Data Using Modified OCM



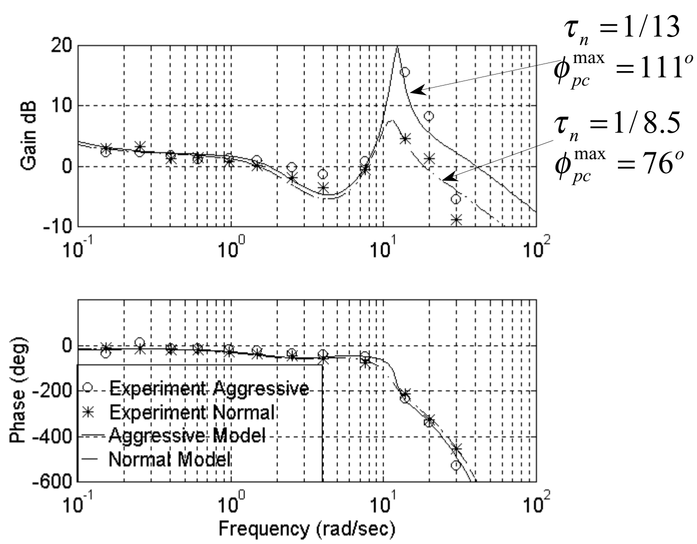
Bacon-Schmidt and NS-2D



Evaluation of NS-2D (USAF/LAMARS)



Aggressive vs. Normal Behavior, Single Pilot (PC Simulation)



Conclusions

- OCM methods have the potential to describe differences in and among pilots in closed loop compensatory tracking tasks for linear controlled elements.
- High frequency roll-off characteristics of the human appear to be higher than 1st order as predicted by OCM.
- Performance and workload metrics extracted from OCM fits to experimental data could provide insight into rating variability and possibly help gauge the validity of ratings.
- Use as a predictive tool to estimate the range of ratings that could be expected from a pilot population by varying time delays and neuromotor lag time constants over a reasonable range.

Mary Shafer:

- Acknowledgements
- Closing remark

I'd like to thank...

- Paul Steinmetz
- Frank Newton
- Everlyn Cruciani
- Patti Pearson
- Dennis Calaba
- Darlene Homiak
- Dave Mitchell
- Moderators
- Presenters
- Attendees
- Tour organizers
- Ed Schneider

In closing:

- “All happy families are alike, but each unhappy family is unhappy in its own way.” Leo Tolstoy, *Anna Karanina*.

- “All good aircraft are alike, but each bad aircraft is bad in its own way.” Mary Shafer

Appendix 1

Pilot-Induced Oscillation Research:
The Status at the End of the Century

NASA Dryden Flight Research Center
Edwards, CA
6-8 April 1999

For well over a century, as long as people have been gliding and flying, aviation safety has been threatened by pilot-induced oscillations (PIOs). As our calendars prepare us for 2000, the time for reviewing the status of PIO research is at hand. NASA Dryden Flight Research Center is pleased to sponsor an open workshop doing just this in a three-day session on 6-8 April 1999.

The last public presentation of PIO research was in 1995 and since then, a number of major PIO research programs have been completed. The results of these programs will be presented at this workshop, as will be the results of other studies, hypotheses, and proposals for further research.

The only restriction is that discussion be limited to safety-related PIO; possible topics include criteria, simulation and flight testing, the pilot's role, design considerations, recent experiences, rate limiting effects and minimization techniques, civil certification, military acceptance testing, analytic techniques, and more. In no way is this the entire list of possible topics and your participation, discussing any topic you feel is relevant, is solicited. It may be that the coffee-break talk alone can offer some insight into a difficult problem you have.

As this is a workshop, with short notice, the expectation is that presentations will not be as formal as conference papers. Copies of the presented material, with whatever supporting material the presenter offers, will be produced. If possible, the entire workshop will be videotaped and copies will be available.

This workshop will be unclassified and open to anyone interested, regardless of affiliation or citizenship. There is no fee for attending. For planning purposes, however, an estimated attendance is required; the response form indicates a variety of methods for responding, however tentatively. Requests to attend must be received by 19 March.

Presentations must be proposed by 5 March. Presentation requirements, as indicated on the response form, must be received by 19 March. Dryden can support viewgraphs, 35mm slides, videotape, and PowerPoint projection (other software requires providing PC-based software). Advance submission of presentation material and supporting material will aid the production of copies for attendees before the end of the workshop. Presentations are nominally scheduled to last 30 minutes, with 10 minutes for questions. Should this be insufficient, please explain the need for more time on the response form.

Please circulate this announcement to anyone you think will be interested. Anyone interested in handling qualities, PIO, aviation safety, pilot-vehicle interfaces, and related topics should be informed of this workshop, as other forums for discussing such topics are no longer common.

Please respond quickly if you think you might attend, particularly if you are considering making a presentation

Pilot-Induced Oscillation Research:
The Status at the End of the Century

NASA Dryden Flight Research Center
Edwards, CA
6-8 April 1999

Attendance (Reply by 19 March, please):

Your full name: ____

Name you want to be called by, for badge ______________________________

Affiliation ____

Address for further ____

mailings about ____

the workshop ____

Telephone ______________________Fax number _______________________

E-Mail address ____

Preferred method for further contact: __ Mail __ E-Mail __ Fax __ Telephone

Presentation (Reply by 5 March, please):

Title ____

____

Co-Authors ____

Presentation media: ___ Viewgraph ___ 35mm slides ___Videotape

___ PowerPoint ___ Other software ___ Other medium

Special requirements

____

Send this form, as soon as possible, to:

NASA Dryden Flight Research Center
Ms Mary Shafer
Mailstop 4840D
P.O. Box 273
Edwards, CA 93523-0273
(805) 258-3396 (workshop only) or (805) 258-3735 (regular number)
(805) 258-2586 (Fax) or email to Mary.Shafer@dfrc.nasa.gov

Pilot-Induced Oscillation Research: The Status at the End of the Century

NASA Dryden Flight Research Center
Edwards, CA
6-8 April 1999

Presentations Information:

All speakers who prepared their presentations with PowerPoint are ***implored*** to bring a copy on disk, plus a duplicate disk, for direct projection. We will have the projector and a computer with the software and would greatly prefer to project the computer version rather than resort to using transparencies. We find that the projected computer image is superior to the projected viewgraph. Speakers who used other software can also project directly if they can bring a laptop or a version of the software that allows reading the images, although such speakers would be wise to bring viewgraphs as a backup on the off chance that this won't work. E-mail me if you didn't use Word or PowerPoint and we'll see what we can do.

Speakers who are using the projection system are asked to bring a paper copy for adding to the handouts; if color is important to understanding the viewgraph, I can make a limited number of color copies, I think.

Any speakers who want more than 30 minutes for their presentations should let me know immediately. More time is available, but I can't allocate it unless I know who needs it.

The preliminary schedule has, as is inevitable, changed, but most of the changes are to the order of presentations within session. Speakers whose presentations have been moved to other sessions have been consulted before the move was made. I'll send out a revised copy by Friday.

SR-71 Tour:

I'm still working on getting permission to have the SR-71 tour. If it is granted, the tour will be during the second half of the time set for lunch on either Wednesday or Thursday and the schedule adjusted accordingly on the other day. For those not familiar with hangar visits, there are just a few obvious rules.

1. Stay 15 ft (5 m) back from the aircraft unless the crew chief gives permission to come closer.
2. Don't touch the airplane without permission
3. Photos are allowed, but flash bulbs (not built-in flashes, but the actual bulbs) are not allowed
4. If we are allowed to look at the cockpit, secure all loose items in shirt and jacket pockets, so that they don't fall into the cockpit and FOD it.
5. Watch your step, as there are cables and hoses on the hangar floor.

Getting Here

For those flying into the Los Angeles area, it will be necessary to drive to Lancaster (where the hotels are) and to Edwards. There are a number of airports in the area but Los Angeles International (LAX) is the most likely destination, although those who can fly into Burbank will find the drive shorter and easier. If you're arriving at LAX, you will take Century Blvd to the San Diego freeway, the 405, and get on it going north (Sacramento is likely to be mentioned) by going under the freeway and then right onto the on-ramp. Go north until the 405 merges with the Golden State freeway, the 5, and keep going north (this is the easy and obvious thing to do). A few miles beyond that take the Antelope Valley freeway, Hwy 14, north. This splits off the 5 on the right side and the city name is Lancaster. Stay on Hwy 14 until you get to Lancaster and then follow the instructions below if you're going to your hotel.

If you're arriving at Burbank, turn left out of the airport and go to the Hollywood Freeway, about two miles. Get on it going north and when you reach the 5, get on it going north. Keep going until you get to Hwy 14 and then proceed as described above.

To get to Dryden, take Hwy 14 north to Rosamond and exit at Rosamond Blvd, going east, to the right. Stay on Rosamond Blvd. In about 10 mi, you'll come to the Edwards AFB guard post, where you must show identification. Those of you with DOD or NASA ID will be waved in when you show it to the guard. Those with other forms of ID should do as directed by the guards. Pre-registered attendees will be on a list for admission. If there's any difficulty, tell the Air Force guard that you're attending the NASA PIO Workshop; if there's any further difficulty, ask the guard to call 258-3273

Dryden is about 10 mi beyond the guard post; stay on Rosamond Blvd though Main Base. The road will narrow to two lanes (from four) and you may think you've gone too far. About a mile after the road narrows, you'll see a number of metal bleachers on the left. The road to Dryden is on the right, just beyond these. There are signs, of course, and you can see Dryden down on the lakeshore. Turn right, cross the railroad tracks, and turn right at the second opportunity, just before the HL-10 lifting body on a plinth. Turn left into the parking lot right after you go by the F-104G, X-29, and two F8s. Walk to Visitor Registration, just across the street from the X-15 mockup, and go to the workshop registration desk.

Amenities:

The room we're meeting in is adjacent to the cafeteria. It is open for breakfast and lunch and also for breaks. The afternoon breaks will begin before the cafeteria closes at 1400.

The Dryden Museum and Gift Shop is in the same building and is open to the public. The Gift Shop sells film in addition to a variety of aviation and space-related souvenirs, including tee shirts, models, toys, pins, photos, and similar goods. They now take credit cards.

The Dryden Exchange, inside the facility, sells stamps and common over-the-counter remedies and toiletries (the cafeteria sells some remedies, too); access is easily arranged. The Dryden credit union can handle minor financial transactions, such as cashing traveler's checks (in US dollars); again, access can be arranged.

Dryden has public tours twice a workday; anyone willing to miss a portion of a session can go on the tour if there's enough space. Additionally, AFFTC runs a tour of Edwards on Friday morning, so anyone with an extra day can do the AFFTC tour on Friday morning and the Dryden tour on Friday afternoon. Let me know if you want to do this, as reservations are required.

Lodging:

The better hotels are in Lancaster, which is 35 mi (and about 45 minutes, counting parking) from Dryden. This list is just a few of them, mostly with restaurants and all the usual facilities. Members of the AAA can find a more complete list in the guidebook for California.

<u>Desert Inn</u>
44219 Sierra Hwy,
Lancaster
661 942-8401
661 942-8950 fax
mkt@desert-inn.com
Government rate $60 + tax, corporate rate $62 + tax

Leave 14 at Ave K, turning right (east), go a little over a mile to Sierra Highway (just before the railroad tracks) and turn left. The Desert Inn is a little more than half a mile, on the left.

Antelope Valley Inn
44055 Sierra Hwy
Lancaster
661 948-4651 (800 528-1234 for Best Western reservations in US)
661 948-4651 fax
Government rate $63 (includes breakfast & 2 bar drinks every day), corporate rate $63 + tax

Leave 14 at Ave K, turning right (east), go a little over a mile to Sierra Highway (just before the railroad tracks) and turn left. The Antelope Valley Inn is about half a mile, on the left.

Inn of Lancaster
44131 Sierra Hwy
Lancaster
661 945-8771
661 948-3355 fax
Government & corporate rate $58.85 (includes breakfast every day, dinner Tuesday and Wednesday)
Leave 14 at Ave K, turning right (east), go a little over a mile to Sierra Highway (just before the railroad tracks) and turn left. The Inn of Lancaster is about half a mile, on the left.

Oxford Inn
1651 West Avenue K
Lancaster
661 522-3050 (800 522-3050 for reservations in US)
661 949-0896 Fax
Government & corporate rate $55 + tax (Continental breakfast and happy hour included)
Marie Callender's Restaurant on premises

Leave 14 at Ave K, turning left (west), going under freeway. The Oxford Inn is on the right, quite close.

The Essex House
44916 10th St. West
Lancaster
661 948-0961
661 945-3821
essexhouse@hughes.net
Government & corporate rate $62 standard room, $74 king, $78 suite (Buffet breakfast weekdays, continental breakfast weekends)

Leave 14 at Ave I, turning right (east) and go a little over a mile to 10th Street West, turning right. The Essex House is about 0.25 mi, on the left.

One loose end to tack down and some information on the local climate for people not familiar with the Southern California High Desert.

For larger PowerPoint presentations that won't fit on a diskette, there are two other options, CD-ROM or Zip. The laptop we'll be using for projecting has both a Zip drive and a CD-ROM (DVD, actually) drive.

Weather and what to wear:

Dryden is an informal place and I suggest that attendees adapt to the local standards. Business/government casual, which for engineers starts here at jeans and tee shirts and goes on to a point just short of dress shirts and ties (and for pilots starts and stops at flight suits), is suggested. I'm sure everyone will reach a proper balance of comfort, casualness, and appropriateness. As it is Spring here, a layered approach is often wisest.

The average high temperature for the week of the workshop is 70 degF (21 degC, if I've done the conversion correctly) and the average low is 42 deg F (5.6 degC). The average precipitation for the entire month of April is 0.01 in. (0.3 mm), so we're unlikely to have more than a trace of rain. I personally expect clear blue skies for the entire workshop. However, there is a fair chance of some wind, in which case the highs will be lower and the lows will be higher and, more to the point, the so-called wind chill factor will make it seem even colder. Right now, on Wednesday, 31 March, we've got a cut-off low in the area and it's blowing about 30 kt, maybe a little more, and the temperature is about 55 degF (13 degC), so I've got a lined jacket instead of the shell I use to keep off the morning chill.

We'll either have lovely spring days with blue skies and comfortable temperatures or we'll have windy, cool spring days or a combination of the two. This is why I suggest layers--a short-sleeved shirt with a wind-proof light jacket over light to medium-weight slacks or trousers. Just in case I've been overly optimistic about the rain, an umbrella might not be a bad idea. However, even at its worst, the weather shouldn't be terrible, just a bit uncomfortable. It is Spring, a freeze is unlikely, and trees and bulbs are flowering. There may even be some wild flowers to see, although we didn't get enough rain in the winter to make a big show and it's too early for the California poppies.

Attached in MS Excel format is the almost-final version of the schedule (agenda). If you can't read this, there's a version with CSV comma-delimited text (agendatxt), although I'm skeptical about its readability. Flat text doesn't seem to be an option.

However, it probably doesn't much matter, as long as you show up at 0800 or so on Tuesday. Everyone getting this e-mail will be on the list for the USAF guards to admit, so there shouldn't be a problem.

I'm looking forward to seeing everyone and I think we're going to have a good time.

We will be allowed to see the SR-71s; I'm now negotiating whether we will be allowed to look inside the cockpit.

Tom Cord is arranging a social event at the Officers' Club (Club Muroc), probably on Tuesday evening. It's not an official event, but attendance is encouraged.

The Weather Channel is currently predicting "cool" temperatures and rain showers on Tuesday, moving out on Wednesday, and warmer on Thursday. This is coming down out of the Gulf of Alaska and may miss us, but probably won't since I've gathered so many people together here. I interpret "cool" as around 50 degF, by the way.

Regards,
Mary

PS. If anything desperate requires you to contact me over the weekend, you may call me at 661 942-7434. MFS

To: Members of RC Branch

There will be a workshop "Pilot-Induced Oscillation Research: Status at the End of the Century" here at Dryden on 6-8 April. I have attached the almost-final agenda (in Excel).

Pat thinks it important that members of the branch participate as much as possible in this and I'd like to invite everyone to stop by for as many presentations and discussion as you can manage. The people speaking and attending are all well known and highly regarded, so we'll have a chance to hear the latest news from the people who really know.

Nothing special is required for Dryden personnel to attend. None of the material presented is classified or limited in distribution. I will have copies of the material presented for those who can't make it, although the discussion is often more interesting and informative than the actual presentations.

I hope to see many of you there.

Mary

Thursday 8 April

Session V: Real-Time Detection of PIO, Moderator Daniel Biezad, Cal Poly, San Luis Obispo

Do We Need Onboard Detection of PIO? David B. Leggett, Air Force Research

Real Time PIO Detection and Compensation. Chadwick J. Cox, Accurate Automation Corp. and Carl Lewis, Robert Pap, Brian Hall, Charles Suchomel

PIO Detection with a Real-time Oscillation Verifier (ROVER). David G. Mitchell, Hoh Aeronautics Inc.

Pilot Opinion Ratings and PIO. Michael Nelson and Tom Twisdale, USAF Test Pilot School

The Need for PIO Demonstration Maneuvers. Vineet Sahasrabudhe and David H. Klyde, Systems Technology, Inc, and David G. Mitchell, Hoh Aeronautics Inc.

Session VI: Flight Results, Moderator John Hodgkinson, Boeing Phantom Works

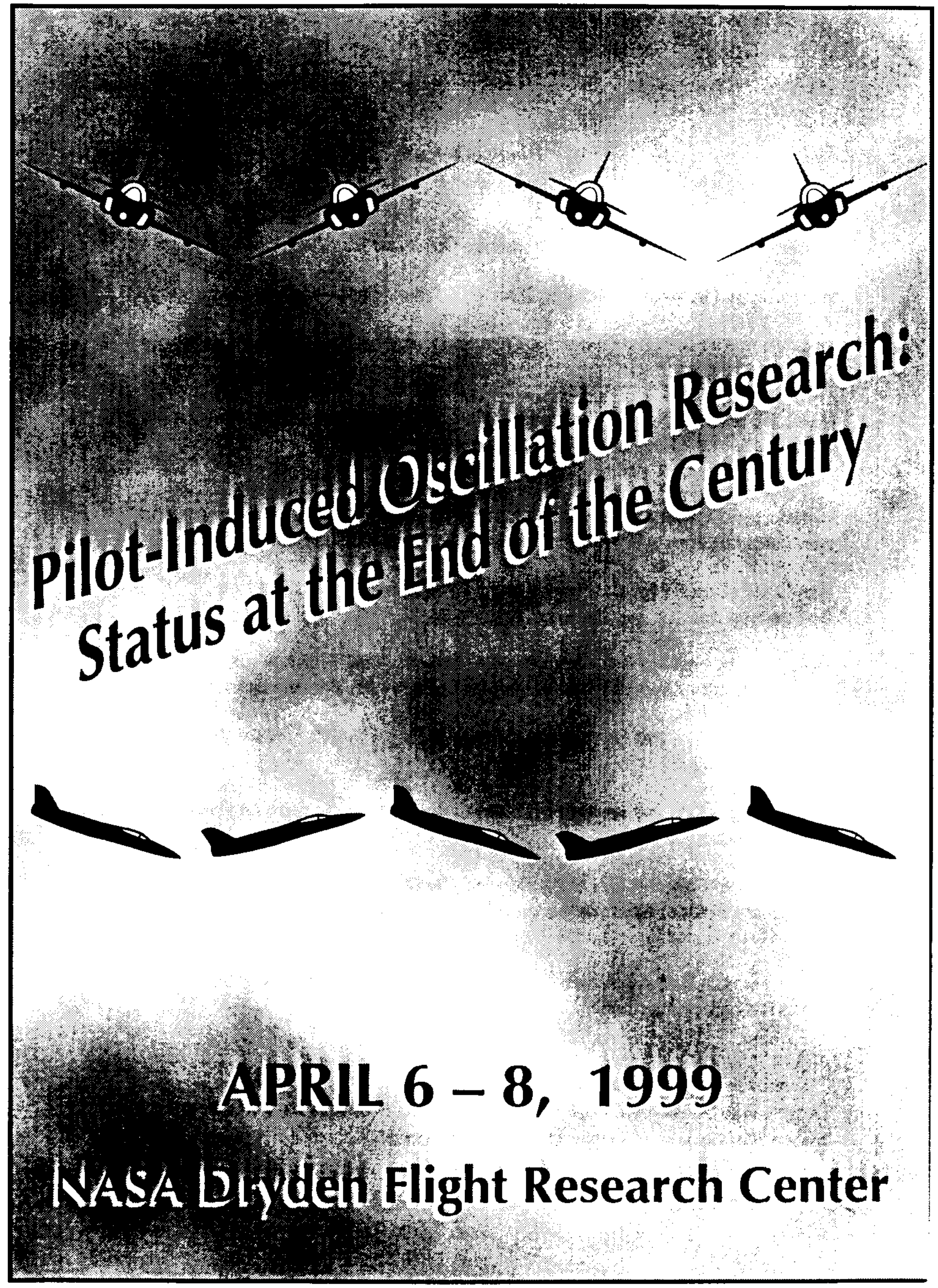
T-45 Ground Handling Qualities. James G. Reinsberg, Boeing St Louis

Extraction of Pilot-Vehicle Characteristics from Flight Data in the Presence of Rate Limiting. David H. Klyde, Systems Technology, Inc. and David G. Mitchell, Hoh Aeronautics Inc.

Comparison of PIO Severity from Flight and Simulation. Thomas J. Cord, Air Force Research Laboratory

A Summary of the Ground Simulation Comparison Study for Transport Aircraft. Terry von Klein, Boeing Phantom Works

Real Experiences in the Frequency Domain. Andrew Markofski and Randall E. Bailey, Veridian Engineering



Tuesday 6 April

Registration (1 hour)

General Remarks Mary Shafer, Workshop Organizer

Welcome by Mr. Kevin Petersen, Director, Dryden Flight Research Center

Session I: PIO Criteria, Moderator Thomas Cord, Air Force Research Laboratory

Modeling the Human Pilot in Single-Axis Linear & Nonlinear Tracking Tasks. Y. Zeyada and Ron Hess, University of California, Davis

Criteria for Category I PIOs of Transports based on Equivalent Systems and Bandwidth. Kenneth F. Rossitto and Edmund Field, Boeing Phantom Works

Bandwidth Criteria for Category I and II PIOs. David G. Mitchell, Hoh Aeronautics, Inc.

Designing to Prevent PIO. John C. Gibson, Consultant, British Aerospace

Session II: Simulation of PIO, Moderator Louis Knotts, Veridian Engineering

Replicating HAVE PIO on the NASA Ames VMS. Jeffery Schroeder, NASA Ames Research Center

Replicating HAVE PIO on Air Force Simulators. Ba T. Nguyen, Air Force Research Laboratory

Prediction of Longitudinal Pilot-Induced Oscillations Using a Low Order Equivalent System Approach. John Hodgkinson and Paul Glessner, Boeing, and David Mitchell, Hoh Aeronautics Inc

Recommendations for Future PIO Simulation Studies. Brian K. Stadler, Air Force Research Laboratory

The workshop will begin at 0800 and end at 1600 each day.
Lunch will begin at about 1115 and last 45 minutes to 1 hour.
There will be a morning and afternoon break.

Wednesday 7 April

Session III: Regulatory Issues, Moderator Al Lawless, National Test Pilot School

FAA's History with APC. Guy C. Thiel, FAA

PIO and the CAA. Graham Weightman

PIO Flight Test Experience at Boeing -- and the Need for More Research. Brian P. Lee, Boeing Commercial Aircraft Co.

The Effects on Flying Qualities and PIO of Non-Linearities in Control Systems. Edmund Field, Boeing Phantom Works

Mitigating the APC Threat - a work in progress. Ralph A'Harrah, NASA Headquarters

Session IV: Flight Research and Test, Moderator Mary Shafer, NASA DFRC

Flight Testing for APC: Practice at Airbus. Pierre Poncelet, Aerospatiale, and Fernando Alonso, Airbus

The Prediction and Suppression of PIO Susceptibility of Large Transport Aircraft. Rogier van der Weerd, Delft University of Technology

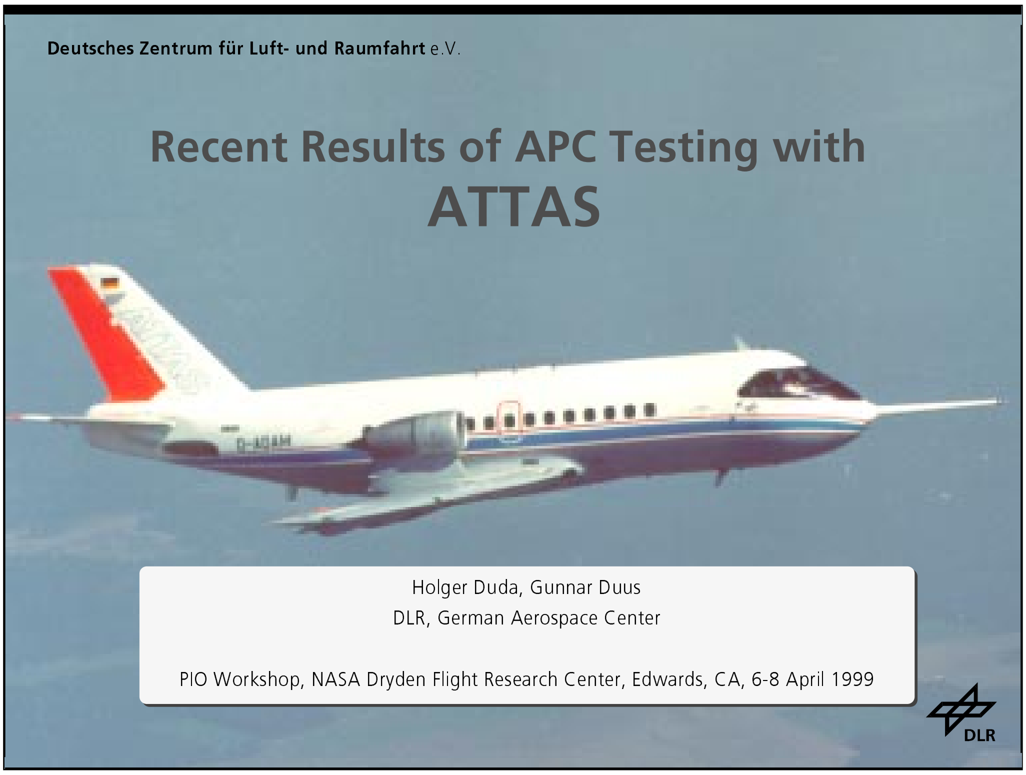
Space Shuttle Orbiter Landing PIO. Pat Forrester, NASA Johnson Space Center

Flight Testing for PIO. Ralph H. Smith, High Plains Engineering

Use of In-Flight Simulation for PIO Testing and Training. Michael Parrag, Veridian Engineering

A Method for the Flight Test Evaluation of PIO Susceptibility. Tom Twisdale, USAF Test Pilot School

Appendix 2



This presentation gives an overview about results of PIO-investigations obtained from a flight test program on DLR's flying simulator ATTAS (Advanced Technologies Testing Aircraft System). ATTAS is a small civil a/c, which has been developed as a full Fly by Wire In-Flight-Simulator with a safety pilot in the right seat.

(This presentation has been prepared by Dr. Holger Duda and Gunnar Duus and myself)

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Contents

- Aircraft-Pilot Coupling
- Prediction of APC
- The OLOP Criterion
- Recent Flight Test Experiments with ATTAS
- Data Analysis Techniques for APC Assessment
- Conclusions
- Future Activities

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PIO Workshop, NASA Dryden Flight Research Center, Edwards, CA, 6-8 April 1999

The contents:

– 1. The aircraft-pilot coupling phenomenon is illustrated briefly. Criteria for APC-prediction are discussed, emphasizing the OLOP-criteria for prediction of nonlinear APC.

– Thereafter the main results of recent ATTAS-experiments, with respect to experiment-design, results and data analysis concepts for APC assessment are discussed.

– Finally the conclusions and DLR's plans for the future are given.

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Aircraft-Pilot Coupling (1)

- Aircraft-Pilot Coupling (APC) is a highly adverse man-machine problem due to disharmonic pilot control inputs.
- The meaning of the acronym PIO was changed from *pilot-induced oscillation* to *pilot-involved oscillations* in order not to blame the pilot.
- Non-linear effects in the flight control system can cause APC problems (*flying qualities cliff*).
- The APC phenomenon contains three main elements: the pilot, the aircraft, and the trigger.
- APC is no pilot failure, but a failure in the flight control system design process.

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– The above list contains the most important key words when talking about APC.

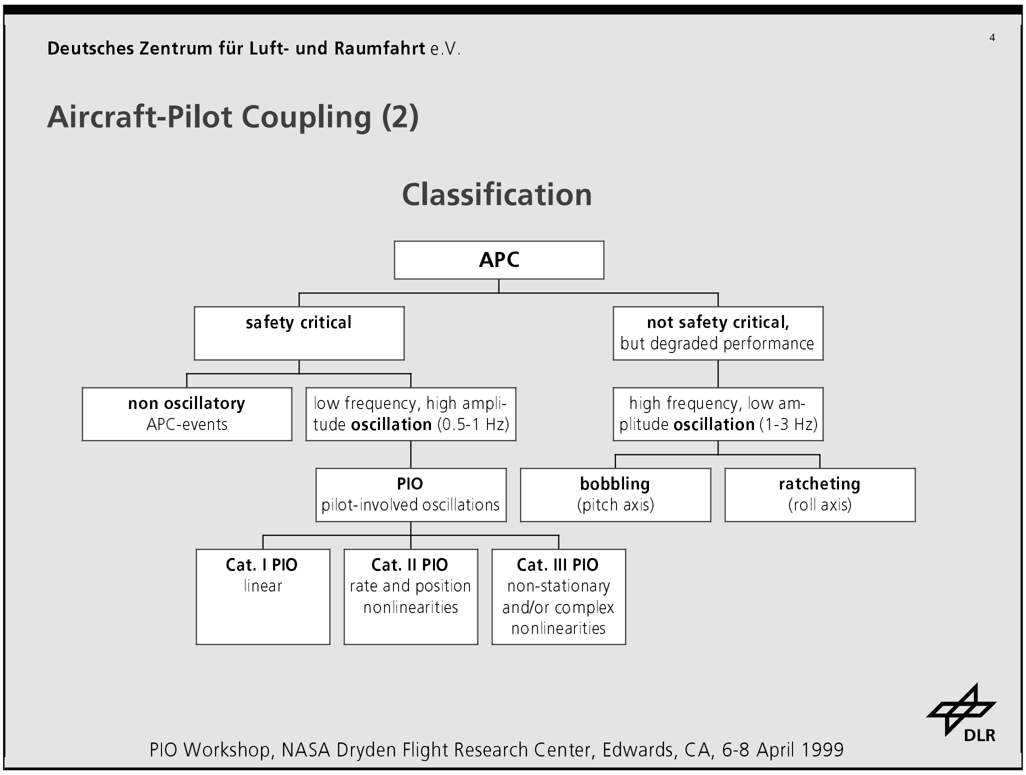
– There is a strong agreement that APC is a highly adverse man-machine problem due to disharmonic pilot control inputs.

– The expression APC was introduced to replace the acronym PIO first. Today APC has a more general meaning than PIO

– We all know well that nonlinear effects in the FCS can trigger APC. This is commonly illuminated by the FQC metaphor

– Further more we can state that an APC contains 3 elements: pilot, a/c and trigger. Pilot is obvious, since without the pilot in the loop no APC is possible. The a/c is represented by the complete Flight Control Systems. The trigger can have different forms, such as NL-effects, or increased task elements, but always causes a sudden change in the closed loop a/c-pilot system dynamics resulting in a misadaptation of the pilot.

– Last but not least: APC is no pilot failure, but a failure in the flight control system design process.



This diagram shows a simple classification (not complete). We can see safety critical and not safety-critical types of APC.

Not critical: We have e.g. the low amplitude-high frequency oscillations bobbling and ratcheting

Critical.: Distinguish between non-oscillatory and oscillatory (were we have PIO three categories)

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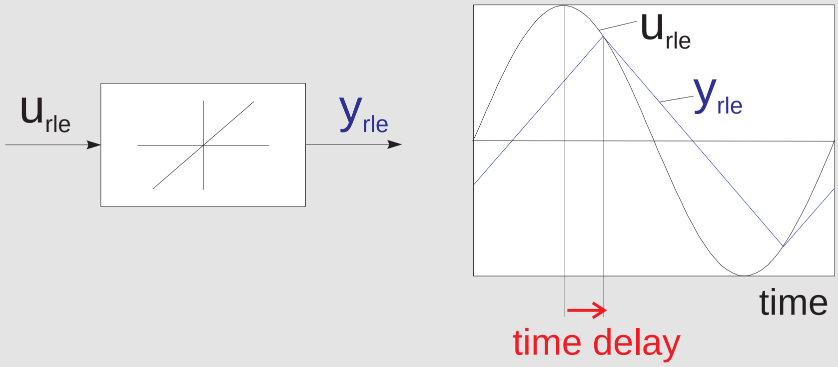
Aircraft-Pilot Coupling (3)

Rate saturation is the dominating nonlinear effect in modern flight control systems triggering APC (Category II PIO)



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– The history of aviation has shown that Rate Saturation is the dominating nonlinear effect in modern flight control systems triggering APC (Category II PIO).This was the background for defining an individual category for APC caused by Rate Limiters > category II PIO.

– The major problem with Rate Saturation is that an additional timedelay is introduced after Rate Limiters onset. The further point is that this additional delay is not constant but amplitude dependent.

Prediction of APC (1)

***The main objective is to predict potential APC problems in the design phase of the flight control system*.**

For that task

several APC prediction criteria are available, such as Neal-Smith, Bandwidth, Phase Rate, Smith-Geddes,

and

a comprehensive handling qualities data base is available, such as the flight test programs Neal-Smith, LAHOS, HAVE PIO, HAVE CONTROL,

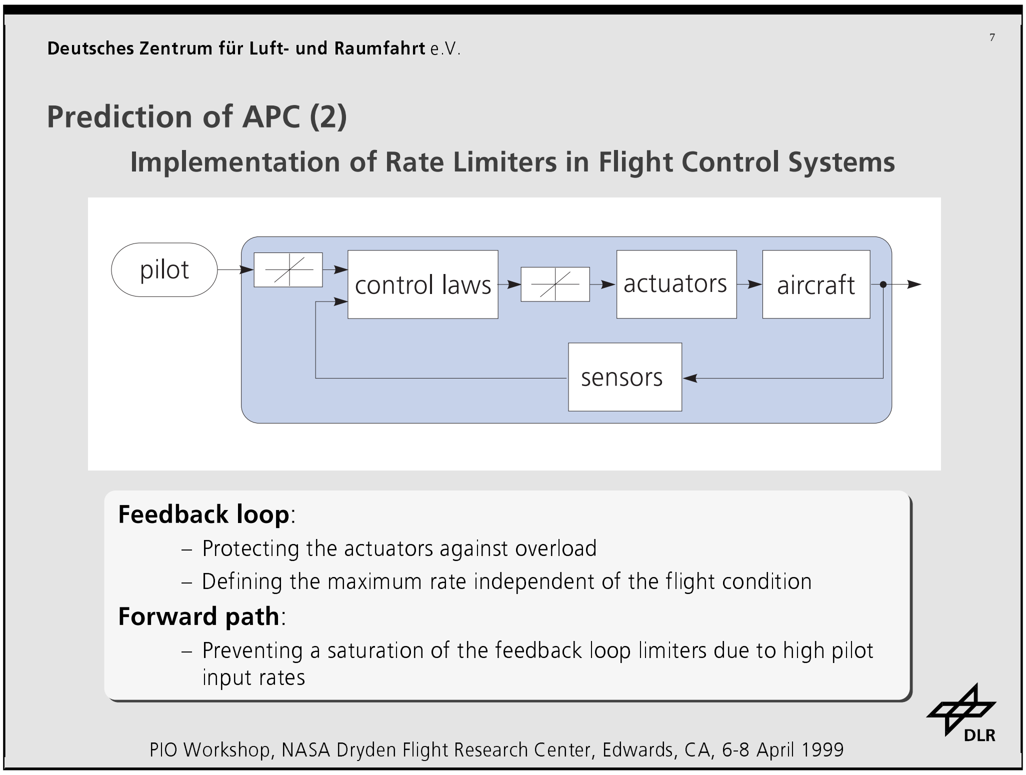
but

most criteria and data bases only address linear effects due to filters and time delays in the flight control system causing a *high frequency phase rolloff*.

The objective of this presentation is to discuss means and methods used to predict potential APC problems in the design phase of the flight control system.

For that task several APC prediction criteria are available, such as Neal-Smith, Bandwidth, Phase Rate, Smith-Geddes.

But most criteria and data bases only address linear effects due to filters and time delays in the flight control system causing a high frequency phase-rolloff. The high frequency phase-rolloff is the main effect causing category I PIO.



But what about category II ?

Let us first have a look at typical implementations of Rate Limiters in modern FCS. We have two typical locations: In the feed-back loop and in the forward path.

In order to predict APC due to these Rate Limiters we have developed the OLOP criteria at DLR.

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The OLOP Criterion (1)

OLOP means the **O**pen **L**oop **O**nset **P**oint of a rate limiter in an aircraft-pilot loop, which is plotted in a Nichols chart.

OLOP is a criterion to predict handling qualities problems due to rate limiting in the flight control system (category II PIO).

OLOP is applicable to the roll, pitch and yaw axes for rate limiting elements in the forward path or in the feedback loop of the flight control system.

OLOP has been developed by DLR based on the describing function technique; the intensity of the jump resonance is highly dependent on the OLOP-location.

*... The **OLOP** criterion has all the hallmarks of the present author's methodology for practical design guidance ...*

John Gibson, 1999

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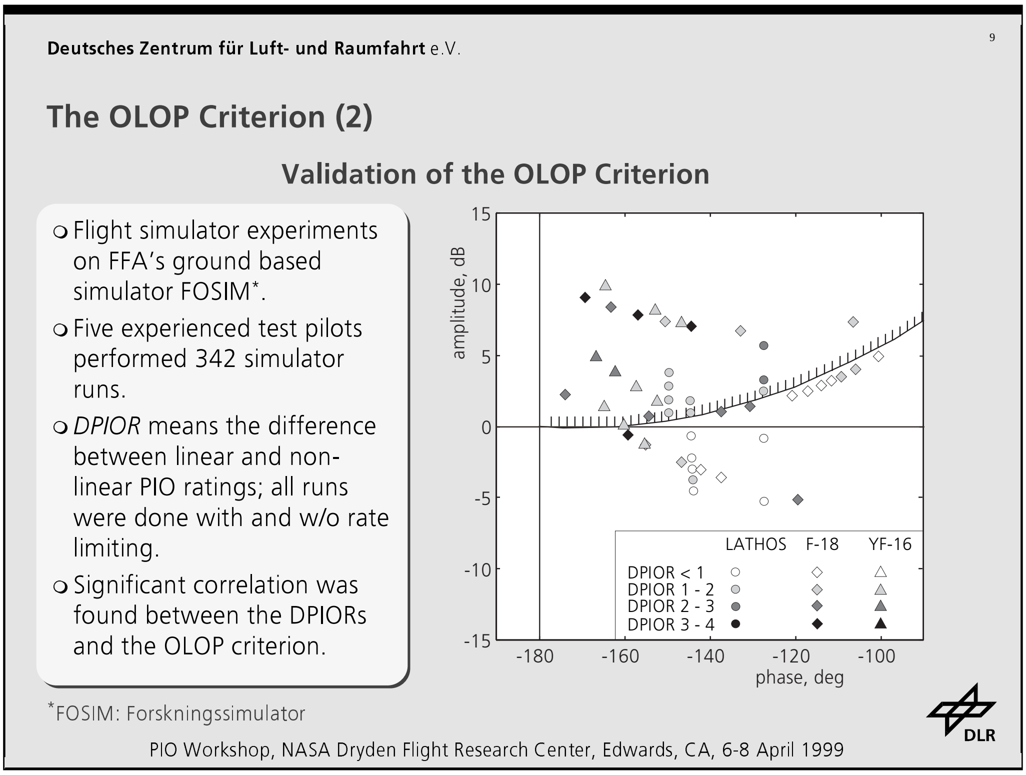
OLOP means Open Loop Onset Point.

The OLOP criterion is capable to predict category II PIO due to rate saturation effects.

It is applicable to all rtelated problems.

OLOP has been developed, based on the Nichols amplitude/phase diagrm It has been shown that the intensity of the jump resonance due to Rate Limiting onset is highly dependent on the OLOP-location in a Nichols chart. For OLOP application no Describing Function technique is required.



Here some high-level information about OLOP are given:

OLOP has been validated by special simulator experiments

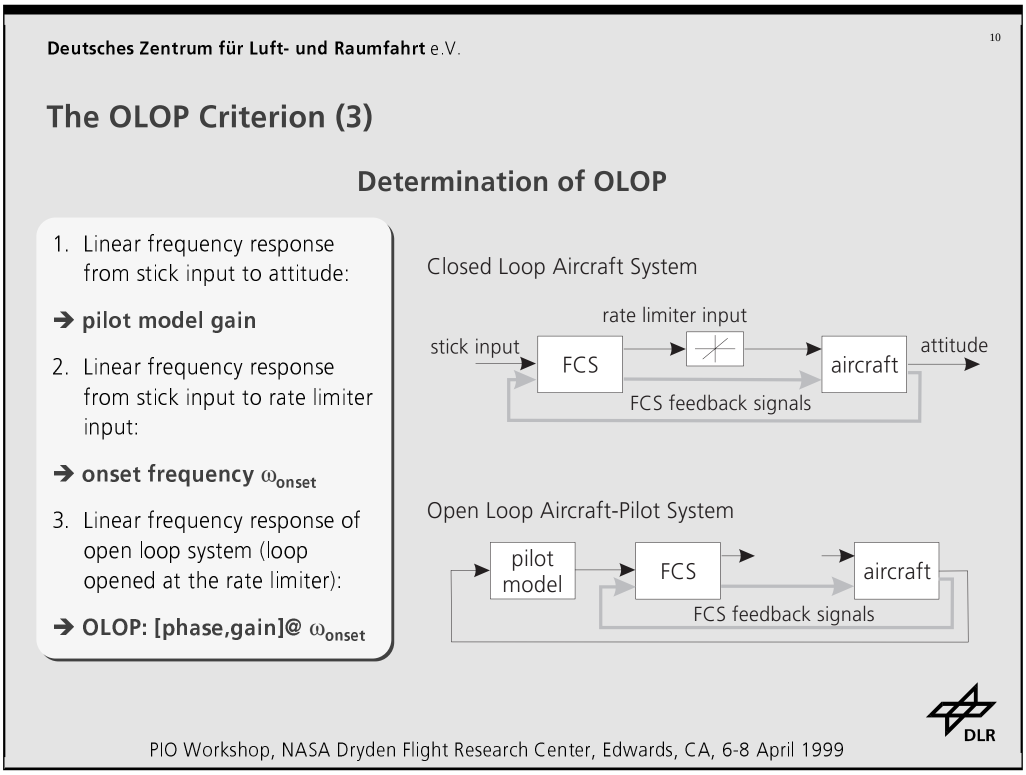
FOSIM simulator was used within a collaboration with the Swedish FFA.

342 test runs (using different configurations in the roll axis based on LATHOS, F-18, YF-16 test pilots) with five test pilots were made.

The results are shown above.

You can see a significant correlation between the OLOP location and the DPIORs

It is important to correlate the DPIORs with OLOP since OLOP only predicts APC due to Rate Limiters effects. It is not correlated with the category I PIO criteria.

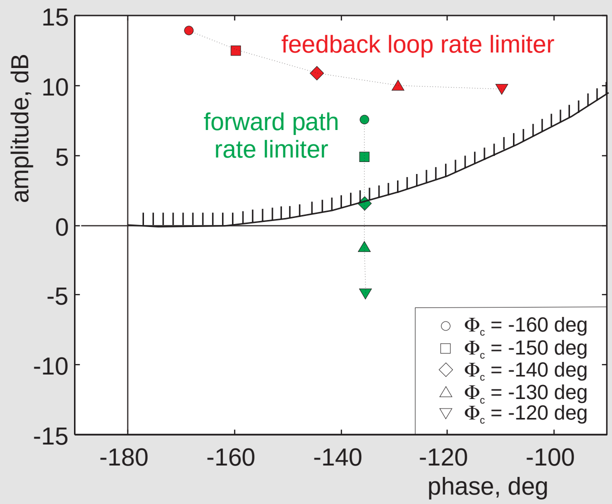


For OLOP applicaation three linear frequency responses are required.

1. From stick to attitude (this is also required for Neal-Smith or Bandwidth criteria) used for the pilot model
2. From stick to rate limiter input > Omega-onset
3. Open loop system including pilot model.

The OLOP Criterion (4)

Influence of Pilot Model Gain



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One special chapter is the pilot model. It is proposed to use simple gain models based on the crossover phase angle Ξc. Further more a range of pilot gains should be investigated.

There are two example configurations, one with Rate Limiter in the feed-back-loop and one with Rate Limiter in the forward path. This is category II PIO prone only for very high pilot gains, which means aggressive pilots. The other configuration (RL in FB-loop) is category II PIO prone for the entire pilot model gain range.

Here we will probably have a problem.

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The OLOP Criterion (5)

Documentation

- Duda, H.: *Effects of Rate Limiting Elements in Flight Control Systems - A New PIO-Criterion*, AIAA-Paper 95-3204, 1995.
- Duda, H.: *Prediction of Pilot-in-the-Loop Oscillations due to rate saturation*, Journal of Guidance, Navigation, and Control, Vol. 20, No. 3, 1997.
- Duda, H.: *Flying Qualities Criteria Considering Rate Limiting,* DLR-FB 97-15, 1997.
- Duda, H., Duus, G.: *New Handling Qualities Database on PIO due to Rate Saturation,* DLR-FB 97-53, 1997.
- Duda, H., Duus, G., Hovmark, G., Forssell, L.: *New Flight Simulator Experiments on PIO due to Rate Saturation*, AIAA-Paper 98-4336, 1998.
- Duus, G., Duda, H.: *Analysis of the HAVE LIMITS Data Base using the OLOP Criterion*, to be presented at the 1999 AIAA-AFM Conference.

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Here a list of the most important documents

– 1995 was the first, where the idea was presented, but the criterion was not fully developed and no data base was available.

– A very extensive report is this one, but in German

– The next papers describe the data base

– And finally we analysed the HAVE LIMITS data base. The results are presented at the 1999 AIAA conference in Portland by Gunnar Duus.

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Recent Flight Test Experiments with ATTAS (1)

Objectives

- Final Validation of the OLOP criterion using flight test data. Identification of pilot model gains in the pitch axis.
- Testing automatic code generation tools for software implementation on the ATTAS experiment computer (Simulink *Real-Time Workshop*).
- Improving flight test evaluation and analysis techniques for APC assessment.

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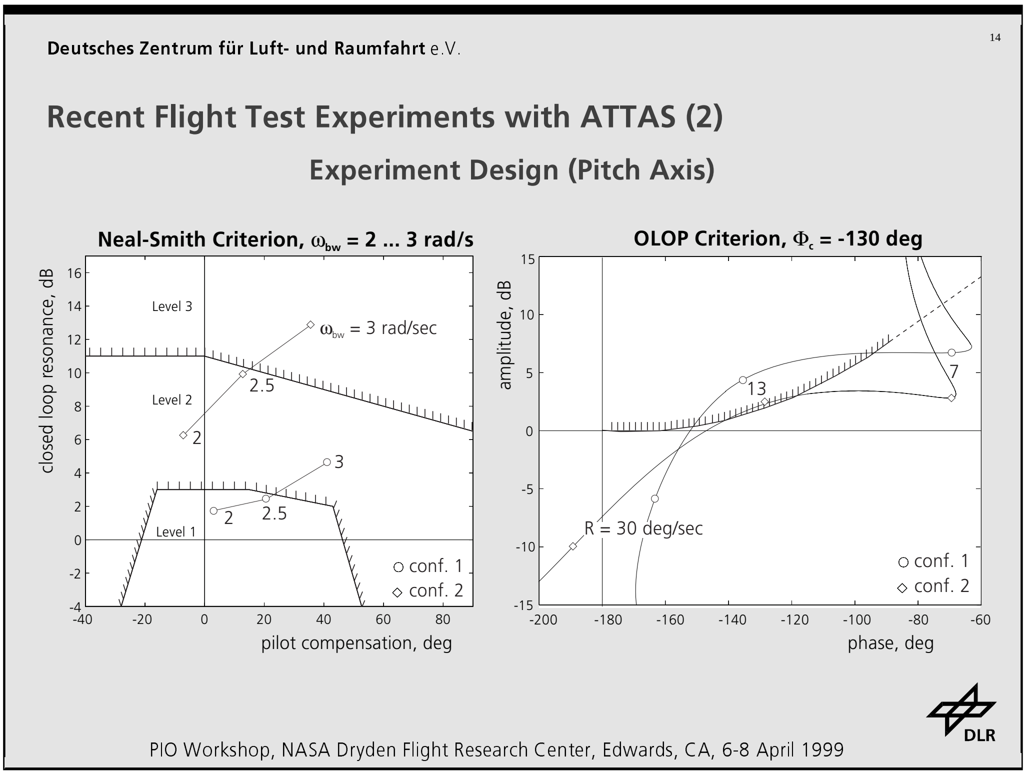
The ATTAS experiments:

There were three objectives:

Although we consider the OLOP criteria as ready we wanted a final validation, especially to get some more experience in the pitch axis.

We did all the design and analysis work in the Matlab/Simulink environment, check Real Time Workshop. Last but not least we plan to develop further our flight test data analysis concepts for APC assessment.



We designed the experiment based on a set of criteria. I will concentrate my talk on the pitch axis, but we did the same thing in the roll axis too.

In the pitch axis we used the N/S and C* criteria in order to define the linear system dynamics and OLOP for the behaviour after Rate Limiters onset. We defined baseline configs. one in L1 and one in L2/3. This is depending on the band width (BW) when N/S is applied. For this type of a/c BW of 2,5 is most relevant. For investigation of Rate Limiter effects we applied 3 max. rates (7, 13 and 30 deg/s) for the elevator deflection.

The diagram shows see the OLOP locations. It is interesting, that with increasing max. rate the category II PIO potential seems to be bigger. This is a point where we were not able to clarify this by the flight test results. We assumed a time delay responsible for this result.

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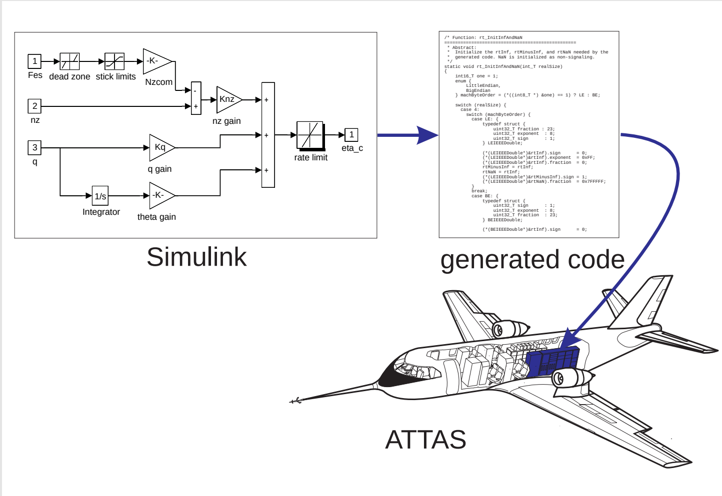
Recent Flight Test Experiments with ATTAS (3)

Software Implementation via Simulink Real-Time Workshop



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This diagram depicts our s/w implementation concept. We developed simple controllers under Simulink. In the pitch axis it is nz or C* law, containing q and nz feedback and one integrator.

Using the Real Time Workshop we simply pushed a button and got a C-code which is implemented on the ATTAS experiment computer.

This is a very exciting technique which we did first time for these experiments. Quite a lot of s/w adaptation work was required, but we now have a excellent basis for future experiments.

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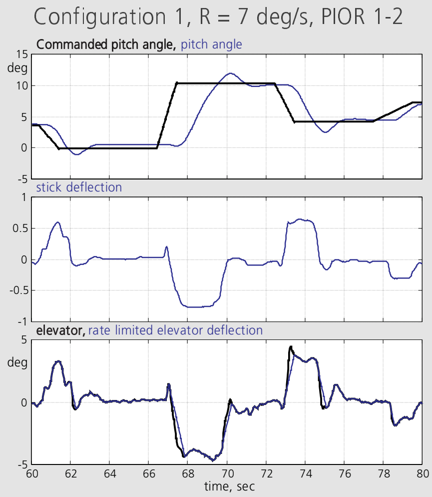
Recent Flight Test Experiments with ATTAS (4)

Experiment Results

- Software implementation via *Real-Time Workshop* works well and provides a very good basis for future experiments.
- Significant correlation between pilot comments and predictions based on the criteria was obtained.
- It is very "difficult" to produce a Category II PIO in the pitch axis for a basically stable aircraft. In the roll axis Category II PIO is more likely.
- Pilot gains were much smaller than expected, especially in the pitch axis.



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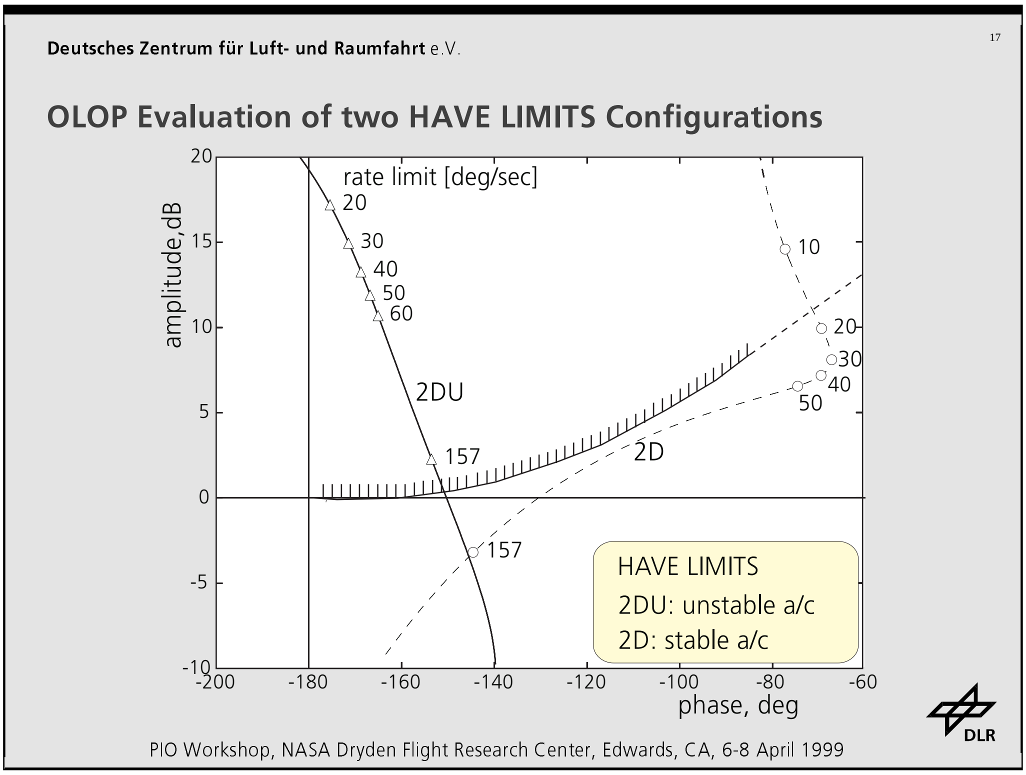
This chart shows the main experiment results:

First the s/w implementation was greatly facilitated using Real Time Workshop.

A significant correlation between pilot comments and predictions based on the criteria was obtained

A very interesting result is, that it is "difficult" or very unlikely to get category II PIO in the pitch axis with stable aircraft.

There is one example - a run with a max. rate of 7 deg/s, which is very low. - The pilot gave a PIOR of 1-2. Here is one explanation: The depicted example shows a tracking task with a commanded pitch angle. Pilot activities show that the pilot gains were much smaller than expected. I will come back to this point later.



Here is one more chart to confirm the statement that category II PIO for stable a/c is very unlikely - the HAVE LIMITS program (to be presented on AIAA 1999).

You see two configs. from HL evaluated with the OLOP: 2D represents a stable a/c, while 2DU represents an unstable a/c. 2D runs into the dangerous area only very low Rate Limitations, while 2DU is category II PIO prone even for quite high max. rates.

This result is well in-line with the FT results obtained in the HAVE LIMITS program. Gunnar Duus will give more details on this study in Portland.

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Data Analysis Techniques for APC Assessment (1)

The objective is to develop procedures for APC-Assessment based on flight test data complementary to the pilot ratings.

Approach

- Identification of simple aircraft and flight control system (FCS) models from the flight test data.
- Evaluation of handing qualities criteria using the identified aircraft and FCS models.
- Comparison of criteria results with pilot comments.
- Identification of pilot models for the evaluation of the OLOP criterion.

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Now I come to the data analysis. The objective is to develop procedures for APC-Assessment based on flight test data complementary to the pilot ratings. The pilot rating is always subjective and it is quite easy not to find a “hidden weakness”. So numerical data analysis is an important factor in order to maximise flight safety.

Our approach is to identify simple a/c- and FCS- models and evaluate Handling Qualities criteria and compare the numeric results with the pilot comments.

Furthermore we identify simple pilot models for application of OLOP.

Data Analysis Techniques for APC Assessment (2)

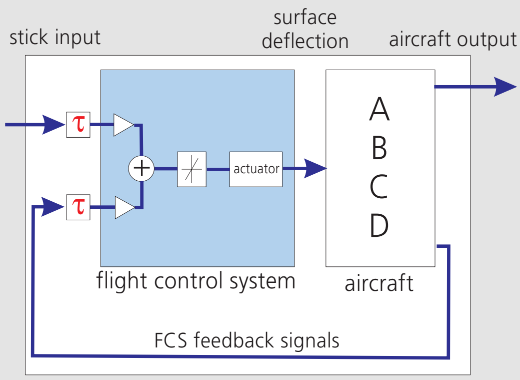
Identification Concept

a) Fourier transforms from stick input to aircraft output signals; approximation of transfer functions

b) Linear aircraft models in the time domain from control surface deflection to aircraft output signals.

c) Linear aircraft-FCS models in the time domain from control stick input to aircraft output signals.

d) FCS time delays using the results from b) and the known FCS gains and rate limits; to be used for OLOP evaluation.



I will now discuss different concepts for a/c-FCS mode identification.

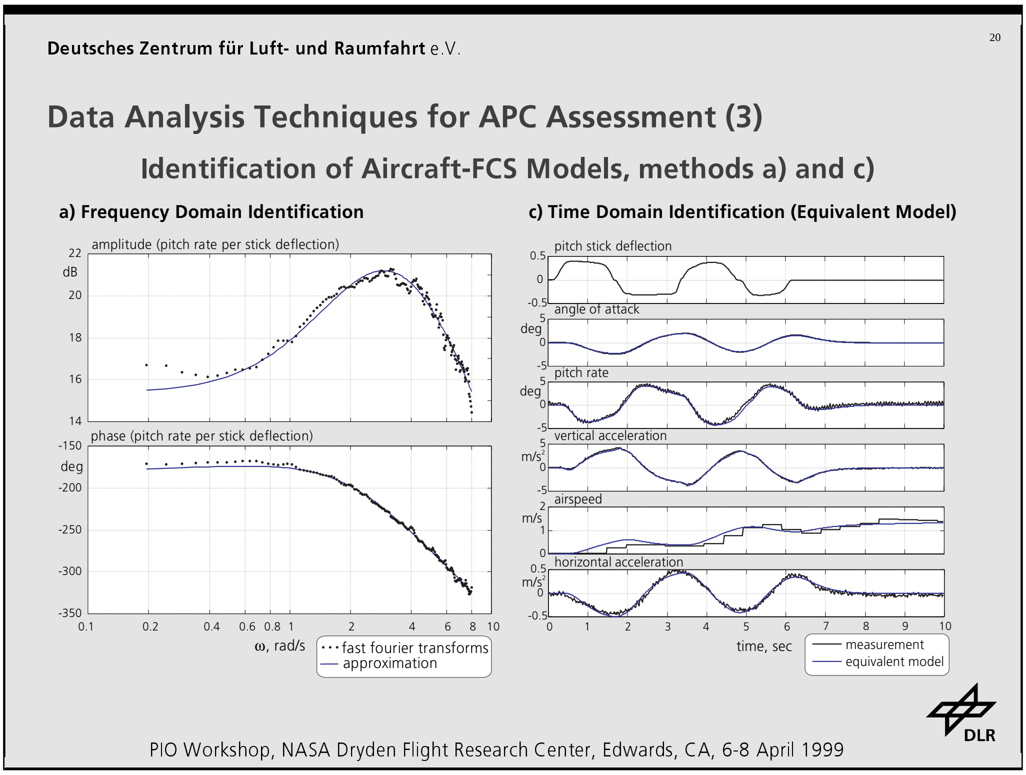
The first one works in frequency domain. Transfer functions are approximated to the fast fourier transforms of the test data.

Method b) is only required for d): it means the identification of linear a/c models using surface deflection as input and a/c reaction as output.

Method c) uses stick signals as input. An equivalent time delay is estimated.

For method d) only delays in the forward path and feedback loop of the FCS ore identified, while the FCS gains, the maximum rate of the limiters and the linear a/c models are fixed.

This technique is required to evaluate OLOP from FT data. OLOP can not be evaluated correctly based on method a) and c) (exception: rate limiters in the forward path).

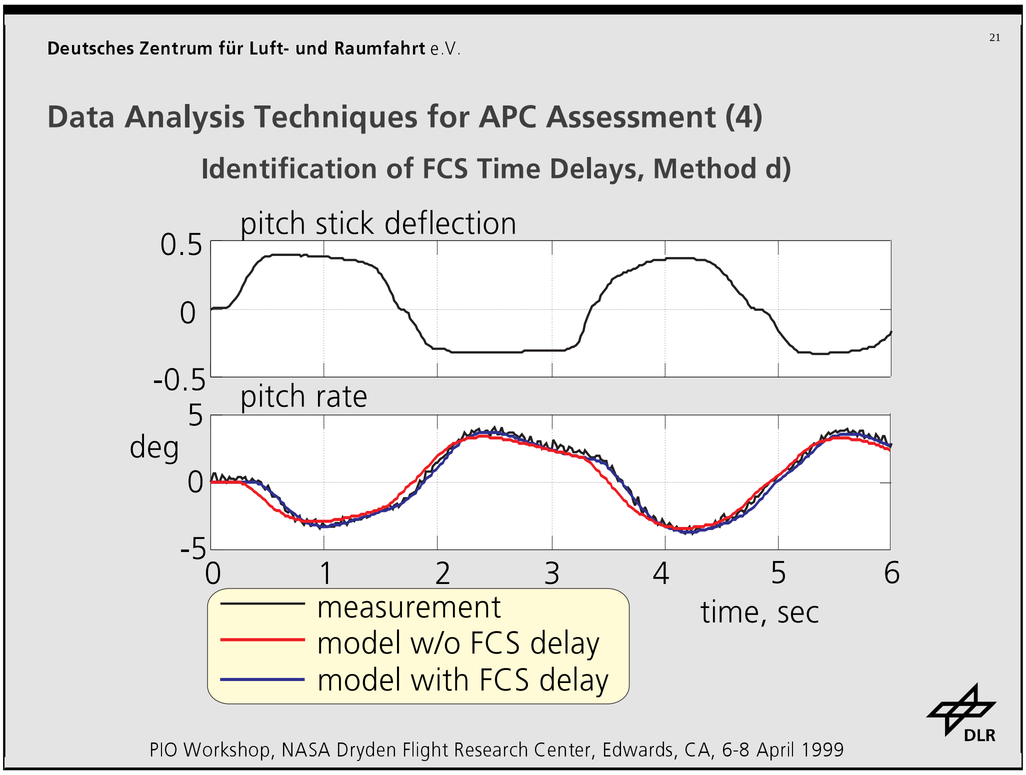


On this chart methods a) and c) are illustrated.

Right: Method a) is a little bit more difficult to apply, you have to decide about the frequency range to be considered. In this case we did the approximation up to a frequency of eight rad/s.

Left: Here you see the identification of an equivalent linear model. Here we have a 3211 input signal, so that it is difficult to include the phugoid motion due to the short time of the run.

It has been shown that an PID of the tracking task (duration = 120 s) is favourable.



This chart shows one PID result of concept d)

The red curve represents the a/c-FCS model response without time delay. The blue curve the response with time delays.

You see that we have a better matching with delay.

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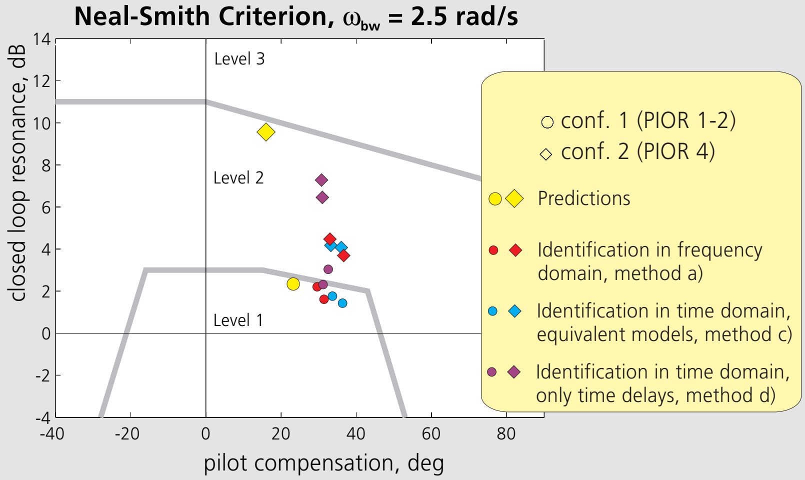
Data Analysis Techniques for APC Assessment (5)

Comparison of Different Identification Concepts



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This chart shows the results of the three Identification concepts for the pitch axis configs. Additionally we see the predictions based on the model and assumed time delay we used before FT. The main cause for the difference between Identification and prediction is the assumed delay.

For config 1 we got very consistent results, but we have some scattering for config 2. This is because this configuration is quite sensitive to additional delays.

Method d) (only ientification of delays) provides the most consistent results compared to the pilot ratings. However we are not quite clear about this config. We need to do some further analysis and FT.

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Data Analysis Techniques for APC Assessment (6)

Identification of Pilot Model Gains

Approach

Parallel simulation of the closed loop aircraft pilot system.

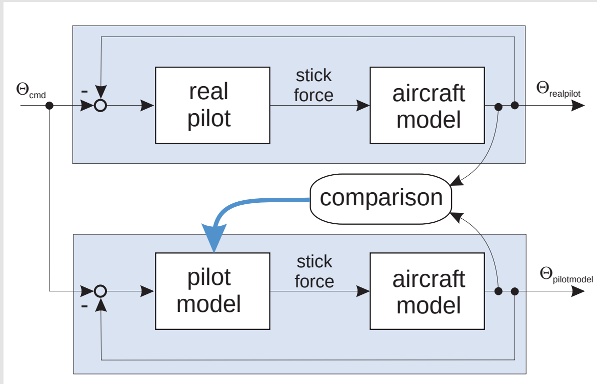
Manual adjustment of pilot gain in order to get "similar" closed loop performance, such as damping and overshoot.

Results

Crossover phase angles for all configurations:

pitch axis: -90 to -100 deg

roll axis: -110 to -120 deg



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For the evaluation of OLOP we need simple pilot models. For that purpose we do a parallel simulation of the closed loop a/c-pilot model. The input model gain is adjusted manually in order to get "similar" closed loop performance, such as damping and overshoot.

In this case we got crossover phase angles significantly lower than expected. For experiment design we assumed -130 deg as medium gain.

In the roll axis this is slightly higher.

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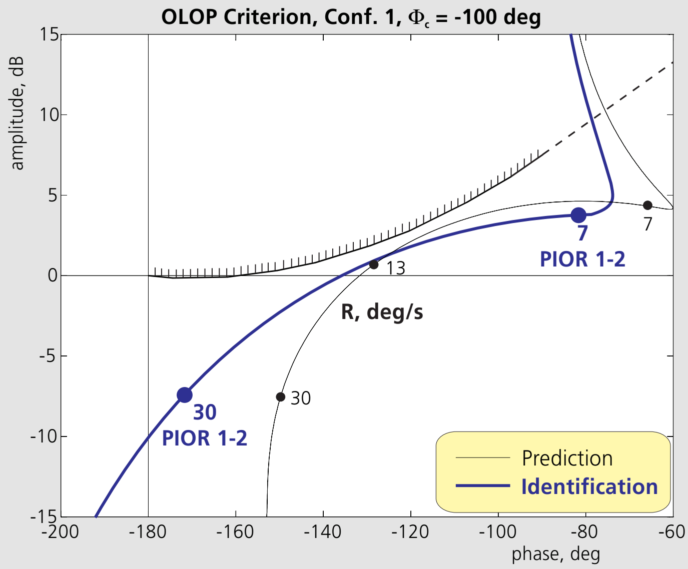
Data Analysis Techniques for APC Assessment (7)



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The identified a/c-FCS and pilot models are used for evaluation of the OLOP criterion. This chart shows config 1- the predicted and identified model for different max. rates.

You see that OLOP does not predict any category II PIO problems, which is well in-line with the pilot comments. The pilot rated this config with PIOR 1-2 for 30 and 7 deg/s max. rate.

We did not fly the 13 deg/s case.

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Conclusions

- Flight test experiments with ATTAS were conducted in order to improve the knowledge base on the OLOP criterion, to test new software implementation procedures and flight test data analysis techniques.
- The pilot comments obtained are correlated with the predictions of the criteria (OLOP, Neal-Smith).
- Software implementation via *Real-Time Workshop* (Simulink) works well and provides a good basis for future experiments.
- Different concepts for flight test data analysis were evaluated; the OLOP criterion was successfully evaluated on the basis of the identified aircraft and flight control system models.

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Conclusions:

We did Flight test experiments with ATTAS in order to improve the knowledge base on the OLOP criterion especially in the pitch axis, to test new software implementation procedures and to improve flight test data analysis techniques.

The pilot comments obtained are correlated with the predictions of the criteria (OLOP, Neal-Smith).

Software implementation via Real-Time Workshop (the C-code generator of Simulink) works well and provides a good basis for future experiments.

Different concepts for flight test data analysis were evaluated; the identified aircraftand pilot flight control system models.

Future Activities

The flight test experiments presented have prototype character; the work is going to be continued with respect to

- Experiments with more APC prone configurations, such as aircraft with relaxed static stability.
- Testing of on-line APC detection and warning algorithms.
- Evaluation of phase compensation filters in order to reduce the time delay due to rate limiting.
- APC demonstration maneuvers.

Long Term Objective

A standard for APC testing of highly augmented aircraft

Criteria to Simulation to Flight Test – and Vice Versa

David G. Mitchell
Technical Director
Hoh Aeronautics, Inc.

Pilot Induced Oscillation Research Workshop
NASA Dryden Flight Research Center
7 April 1999

Outline

- Steps for minimizing PIO risk
- Assessing risk if a PIO occurs
- A possible PIO rating system
- Pilot variability in PIO simulation
- Some recommendations

Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. Use criteria to focus preliminary simulations
4. Use early flight data to update sim. model
5. Repeat steps 1 – 4
6. Use simulation to apply criteria for large inputs
7. Use criteria to focus preliminary flight tests
8. Use real-time onboard detection for early warning
9. Repeat steps 1 – 8

Be Prepared for PIO

- Military procurements represent a dichotomy:
  - Projects adopt success-oriented scheduling
  - Evaluators expect to encounter PIO in flight test
- PIOs will almost always occur
  - Should not be a surprise
  - Testing must be adopted to look for them
- The more advanced the aircraft (unstable, multiple effectors, multi-purpose effectors, complex augmentation) the greater the potential for catastrophic PIO

Be Prepared for PIO (concluded)

- **Pilots must be a part of the process**
  - **Familiar with the phenomenon**
  - **Aware of potential through all phases of testing**
- **PIO is not an operationally relevant event**
  - **Test pilots' job is to go beyond normal operations**
  - **If test pilot won't push the airplane, rest assured that some unsuspecting fleet pilot will**
  - **Any flight test can be a test for PIO tendency**
- **If a PIO occurs, there must be a way to assess risk of continuing flight testing before a fix is found**

Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. **Apply criteria to design**
   - As early as possible in design process
   - If you apply valid criteria and your airplane fails, it doesn't mean the criteria are bad
3. Use criteria to focus preliminary simulations
4. Use early flight data to update sim. model
5. Repeat steps 1 - 4
6. Use simulation to apply criteria for large inputs
7. Use criteria to focus preliminary flight tests
8. Use real-time onboard detection for early warning
9. Repeat steps 1 - 8

Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. **Use criteria to focus preliminary simulations**
   - Don't spend time in areas where criteria are easily met
   - If criteria predict PIO -- fix the design!
4. Use early flight data to update sim. model
5. Repeat steps 1 – 4
6. Use simulation to apply criteria for large inputs
7. Use criteria to focus preliminary flight tests
8. Use real-time onboard detection for early warning
9. Repeat steps 1 – 8

Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. Use criteria to focus preliminary simulations
4. **Use early flight data to update sim. model**
   - It should contain all known nonlinearities and limits
5. **Repeat steps 1 - 4**
6. Use simulation to apply criteria for large inputs
7. Use criteria to focus preliminary flight tests
8. Use real-time onboard detection for early warning
9. Repeat steps 1 - 8

Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. Use criteria to focus preliminary simulations
4. Use early flight data to update design model
5. Repeat steps 1 – 4
6. **Use simulation to apply criteria for large inputs**
   – Frequency sweeps to control limits
   – Even if sim. is doubtful for PIO, it can be useful for applying inputs beyond those considered safe in flight
7. Use criteria to focus preliminary flight tests
8. Use real-time onboard detection for early warning
9. Repeat steps 1 – 8

Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. Use criteria to focus preliminary simulations
4. Use early flight data to update design model
5. Repeat steps 1 - 4
6. Use simulation to apply criteria for large inputs
7. **Use criteria to focus preliminary flight tests**
8. Use real-time onboard detection for early warning
9. Repeat steps 1 - 8

Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. Use criteria to focus preliminary simulations
4. Use early flight data to update design model
5. Repeat steps 1 – 4
6. Use simulation to apply criteria for large inputs
7. Use criteria to focus preliminary flight tests
8. **Use real-time onboard detection for early warning**
   – Tomorrow morning
9. **Repeat steps 1 – 8**

Assessing Risk if a PIO Occurs

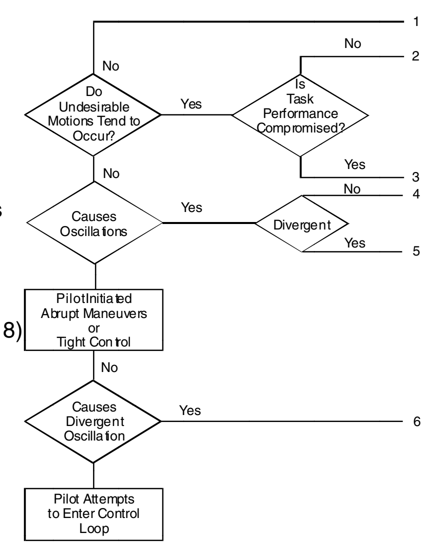
- If PIO occurs in the development process, it must **always** be treated with concern
  – Fix the problem!
- It may be necessary, and possible, to continue the development effort
- Risk is a function of several factors:
  – Category of PIO
  – Severity of PIO
  – Frequency of occurrence and duration of PIO

Reducing Risk: Categorize the PIO

- **Category I (linear):**
  - **it should be possible to quickly identify causal factors**
  - **Lowest risk to continued operation**
- **Category II (rate limiting or other saturation):**
  - **More difficult to identify causes**
  - **Risk depends on other factors:**
    - **Flight condition/aircraft configuration -- avoidable?**
    - **Consequence of saturation -- unstable airplane?**
- **Category III (nonlinear with mode switching):**
  - **Highest risk, factors similar to Category II**

Current PIO Tendency Rating Scale

- Problems with scale
  - Does not mention “tendency”
  - PIOR = 2, 3: not relevant to PIO
  - PIOR = 4: no indication of severity
  - Attempts to mix handling qualities with PIO assessment
- Examples:
  - Pitch bobble (PIOR = 4) with inadequate control power (HQR = 8)
  - Severe (but not divergent) PIO (PIOR = 4) that is unacceptable (HQR = 8)



A Possible PIO Rating System

Severity	Frequency of occurrence	Demands on pilot	Overall assessment
Dangerous (bail out)	Never stopped	Couldn't prevent it (abandon airplane)	What airplane?
Severe (abandon task)	Most of the time	Couldn't prevent it (Abandon task)	Intolerable for the task (fix it)
Moderate (can't ignore it)	Occasional	Prevented or alleviated by technique (task performance compromised)	Objectionable (warrants improvement)
Mild (can ignore it)	Only a very short time	Prevented or eliminated by technique (task performance not compromised)	Tolerable (satisfactory without improvement)
None	Never saw one	No tendency to induce oscillations	What PIO?

PIO Rating System Allows for Risk Assessment in the Development Process

- Example: PIO Severity vs. Frequency of Occurrence

Severity	Frequency of occurrence: Never stopped	Most of the time	Occasional	Only a very short time	Never saw a PIO
Dangerous (bail out)	High	High	High	High	
Severe (abandon task)	High	High	Moderate	Moderate	
Moderate (can't ignore it)	High	Moderate	Moderate	Low	
Mild (can ignore it)	Moderate	Moderate	Low	Low	
None					

Pilot Variability

- **Variability in pilot opinion is well-documented in handling qualities experiments**
  - **Test pilots have varying backgrounds, expectations, flying styles**
  - **This is good! Fleet pilots will be even more diverse**
- **Variability is magnified when it comes to PIO tests and exposure of PIO tendencies**
- **Monitor pilot performance for tracking tasks**
  - **Expect variability in performance (example: recent sim.)**

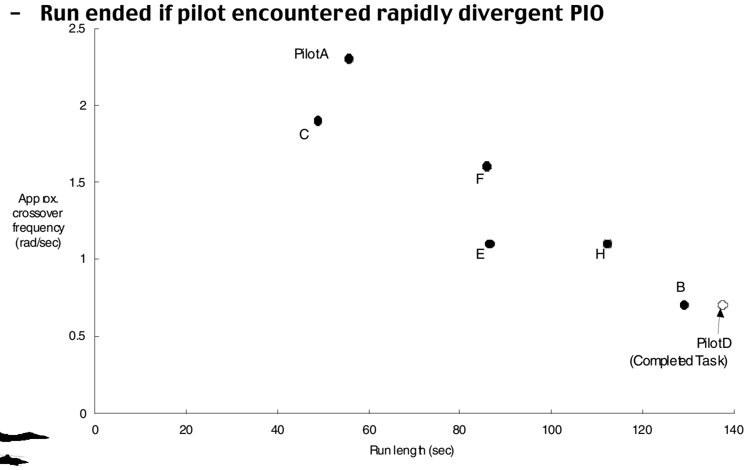
Pilot Variability in PIO Simulation

- Example: HAVE LIMITS Config 2DU, 20-deg/sec RL, discrete tracking task, flown on USAF LAMARS simulator
- Some (minor) differences in setup between sim. and flight
- Results below are typical of sim. (10 pilots total)
  - Different pilots encountered PIO at different rate limits

Facility	Pilot I.D.	HQR	PIOR
NT-33A (Flight)	1	10	6
	2	10	6
	3	10	6
LAMARS (Moving-base simulation)	A	10	5
	B	10	5
	C	10	6
	D	***2***	***1***
	E	10	6
	F	10	5
	H	10	5

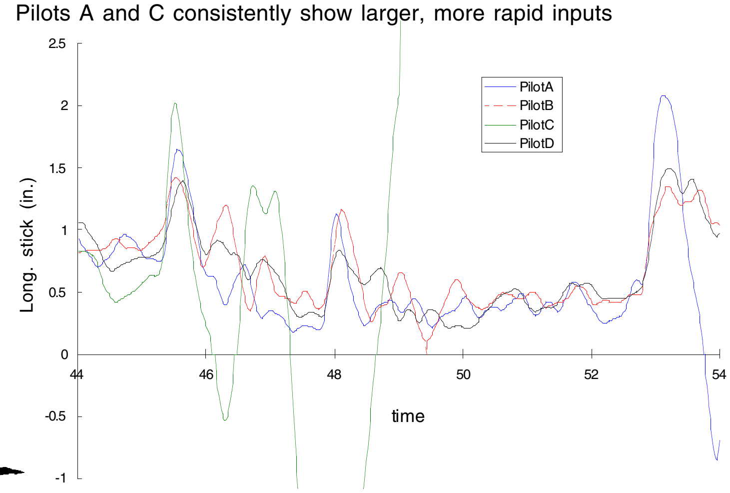
Pilot Variability in PIO Simulation

- **Plot shows measured crossover frequency (q/q_{error}) from discrete tracking task vs. total run time**
  - **Task started at t = 10 sec, ended at t = 138 sec**
  - **Run ended if pilot encountered rapidly divergent PIO**



Pilot Variability in PIO Simulation

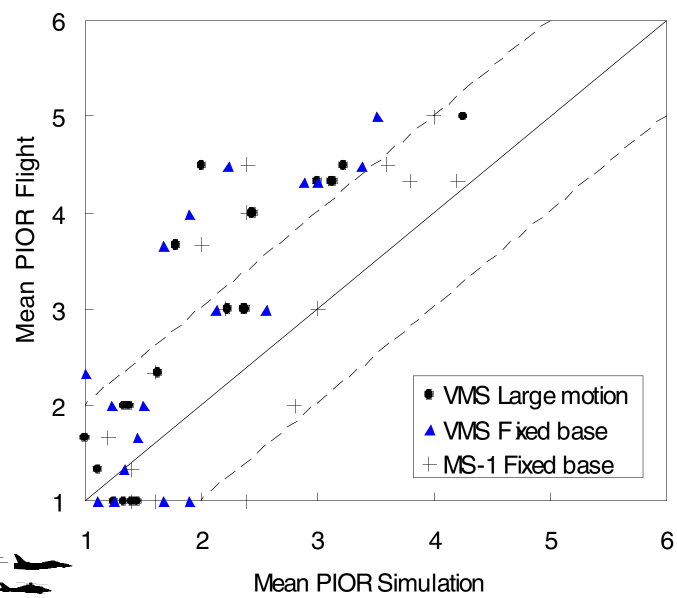
- Ten-second sample of long. stick for two highest-crossover pilots (A and C) and two lowest-crossover pilots (B and D)
  - Pilots A and C consistently show larger, more rapid inputs



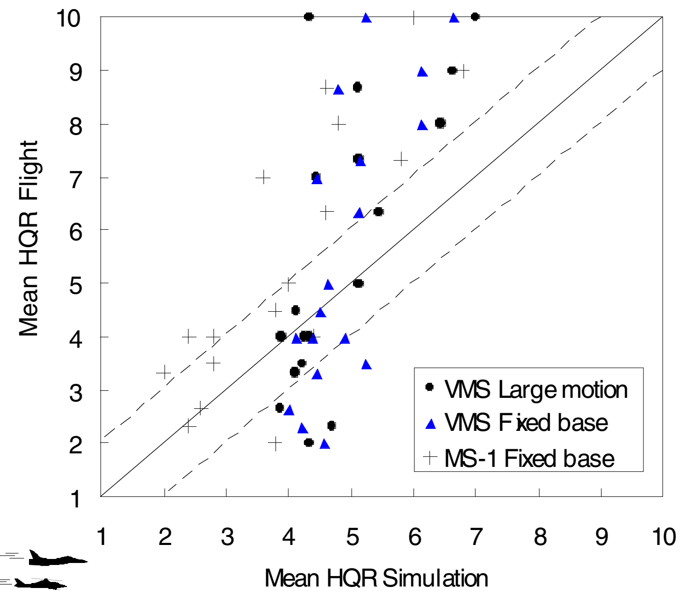
Amplitude of PIO

- Monitor time-history data for evidence of PIO
  - Pilots aren't always aware of PIO on simulator
  - Events that seem mild to the pilot may be severe in flight
  - Work with the pilot as much as possible!

HAVE PIO Rating Comparisons: PIOR

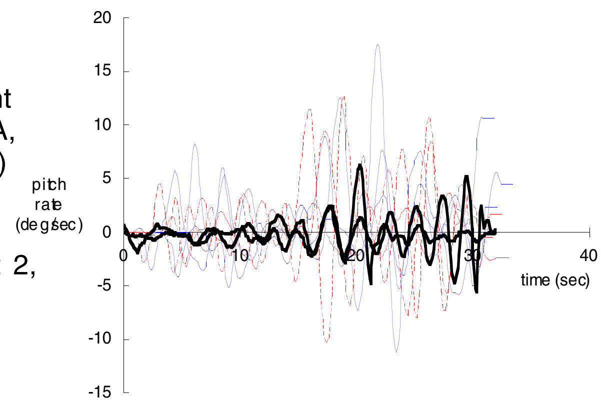


HAVE PIO Rating Comparisons: HQR



PIO May Be More Severe in Simulators

- Black lines: flight program (Pilot A, PIOR 6, HQR 10)
- Red and blue lines: MS-1 simulation (Pilot 2, two sessions, PIOR 4, HQR 6)



Recommendations

- Make maximum use of criteria, simulation, and flight test
- Simulation has value as an adjunct to flight
- Be prepared for PIO
- Assess risk for continuing if PIO is encountered in the development process
- Expect pilot variability
- Look at both qualitative and quantitative information from simulation
  - Ratings tend to be better
  - PIOs may be more severe

Appendix 3

Designing to prevent safety-related PIO

PIO Workshop, NASA Dryden, 6th - 8th April 1999
J C Gibson
British Aerospace Warton (retired), Consultant

Introduction

Though PIO is not a new phenomenon, its current notoriety has been acquired in the past two decades mainly from the all-too frequent serious and sometimes catastrophic examples exhibited in fly by wire aircraft. Such severe examples were a rarity in the earlier "classical" aircraft with conventional control systems. Yet the fly by wire technology had brought with it the power to provide almost any desired handling response qualities. PIOs and sometimes other handling problems of the "high order" type (to distinguish them from the usually much less severe "low order" types possible with conventional dynamics) were actually not generic to the technology as was commonly believed at one time but were inadvertent artefacts of the control system designers. Since the PIO characteristics were "designed in", they can also be "designed out".

The intellectual rigour necessary to prevent PIO by design must be spread out far beyond the discipline of the control law specialists. Section 9 of Reference 1 discusses the team approach essential for the design and evaluation process, and notes the many failures that have resulted from neglecting this. The repeated examples indicate that newcomers to the fly by wire field have found it difficult to believe that the problem could happen to them, and so have not implemented a meticulous anti-PIO design policy. Safety-related, high-order type PIO is not a problem with no practical solution, preventable only by good luck. The author's 1978 paper on the Tornado PIO in 1976 and its solution (Reference 2) was greeted with surprise, since it was not normal in the conference circuits to admit to such a problem even though it was widespread. The latter head-in-the-sand attitude probably contributed to the continuing occurrence of safety-related PIO, and only more recently was the author's example followed by what is now a flood of data and information on the problem.

The author's own brush with PIO and its solution led to a design methodology to eliminate it in future projects. The success of this was demonstrated from the early 1980s onwards by a series of highly unstable aircraft with digital FBW control, namely the Jaguar FBW demonstrator, the EAP demonstrator and the Eurofighter 2000. Each took to the air with a growing certainty that safety-related PIO would not be experienced or even be possible, a certainty that proved to be justified. The rather simple physical principles of control system design for PIO prevention are discussed in Reference 3.

Use and misuse of specifications

Designers are very likely to get into trouble if they simply design to satisfy customer specifications. It is not practical to impose specification criteria for handling qualities design in sufficient detail to ensure good handling qualities while not unnecessarily restricting other design possibilities that may actually improve on the classical response types. It is not the business of a government department to design control systems. Practical specifications provide some "must have" requirements, but one that tries to cover too much ground at once with too few parameters risks allowing unsatisfactory behaviour to slip through if it is used as the only design guidance.

Perhaps the best known example is the specification for short period frequency versus n/α. Level 1 handling has never been achieved with frequencies near the upper limit, except for good landing approach control. The latter is most unlikely with minimum allowable frequencies, but good handling has been achieved at higher speeds with lower frequencies.

Another example in Figure 1 is from generic ASTOVL handling research for the jet-borne hovering phase on a high fidelity motion platform. Two of the cases are plotted on an attitude response mode criterion from the rotary wing aircraft specification ADS-33C. This criterion quantifies the handling by the bandwidth and high order effects by the phase delay. Both cases, assessed in the task of lateral translational control, are nominally second order roll attitude responses with a bandwidth of 6 radians per second. Their actual bandwidth decreases with increasing phase delay, which was created by an additional second order lag to represent high order effects. This generic fourth order model format was derived from a design study for the VAAC Harrier research aircraft and represented its high order system dynamics very accurately.

However, the results were not what the criterion would lead one to expect. In case 1(a), as the bandwidth decreased with increasing phase delay, the translation task handling qualities remained constant. These qualities were found to be related to specific time response characteristics that remained effectively unchanged from the baseline bandwidth case. There was an increasing untidiness in attitude control induced by the high order lag, though the effects were acceptable over the range tested. Case 1(b) with higher bandwidth, despite remaining completely within the criterion Level 1 region, deteriorated into severe attitude control PIO, exacerbated by lateral acceleration forces on the stick and pilot's arm with the cockpit mounted on top of the platform. The cause lay in the high PIO gain of the attitude frequency response, which is not accounted for by this criterion. The only difference between the cases was that 1(a) had a nominal mode damping of 1·0 and 1(b) had a damping of 0·5.

The criterion broadly quantified the handling of Case 1(a), but it was misleading either as a contract specification or as a design criterion when applied to circumstances presumably not envisaged in its original derivation. It is not known if it was tested for responses with low damping, for example, even though this is permitted elsewhere in the specification.

Potential difficulties can be caused by any other limited-parameter criterion. Figure 2 shows the pitch attitude Nichols plots for the YF-17 as tested by Calspan, in the original severely PIO-prone form and the very satisfactory modified version. To the informed eye, the bad and good natures of the respective responses are instantly obvious from the presented detail alone, but it is necessary to have some formalised criteria to quantify this. The modified case was one of the small number of examples with excellent handling around which the author developed the so-called "Gibson criteria" boundaries in Reference 4 from 1982, the one for landing approach being shown in the figure. The boundaries did indeed capture much of the essence of good handling, but were narrowly constrained and were later found to exclude other perfectly acceptable response shapes. Similar problems arose with the so-called "Gibson criteria" time response observations in Reference 4, which again were derived from a fairly limited set of cases. The author also learned the hard way that sometimes others of a dogmatic frame of mind could find it difficult to accept a response that did not entirely satisfy the boundaries "because it violates the criterion", despite his protestations that they were intended as indicative guidelines and not absolute go/no-go limits.

Nevertheless these criteria appear from the literature to have been of assistance to a number of other designers, and were an essential grounding to the author's later design methodology described in Reference 3. In this, there is a much reduced emphasis on attitude frequency response "shape" boundaries because they inherently change their characteristics with increases in true speed and altitude. The nature of pitch behaviour in the "general handling" region of Figure 2 is richly illustrated for design purposes by time responses such as flight path time delay, attitude dropback and pitch rate overshoot, which cannot be quantified directly from the frequency response even though they may be obviously present by visual inspection. On the other hand, while high order PIO tendencies are easily observed by a lag in the time domain pitch acceleration response, they are more clearly delineated in a detailed analysis of the frequency response characteristics in the "safety-related PIO" region of Figure 2, independently of the general handling. All this is discussed in Reference 3. (Time responses are an excellent design tool, irrespective of their unsuitability for flight test analysis.)

A variety of delay criteria have been promoted, of which phase delay (or the average phase rate in the author's terminology) is the most accurate measure of the actual dynamics that may lead to PIO, particularly of Type 1 though obviously these may in turn lead on into Type 2 or Type 3 PIO. It is doubtful if such criteria have any meaning for analysis of large amplitude responses with non-linear actuation effects, however. The author found it unprofitable to attempt the laborious time response analysis for phase delay in this regime.

The primary importance of phase delay is to indicate a significant lag in the initial rotational acceleration time response to a pilot's control input which may lead to a Type 1 PIO. If this diverges into the actuator saturation regime, the PIO continues at a decreasing frequency which remains uniquely related to the 180 degree lag in attitude as the non-linear effects become more pronounced with increasing amplitude. If on the other hand a large saturated PIO bursts into life with no intervening growth from small beginnings, then it instantly locks on to the PIO frequency in the same way. In neither case is there any significance in the rate of phase angle variation over a range of frequency beyond the PIO, which in effect is phase delay. What does matter is the manner in which the attitude response at the unique PIO frequencies varies from the linear case as the pilot's input amplitude increases.

The handling qualities specifications known to the author do not address the safety-related PIO problem directly, other than to require that it must not occur. These specifications are generally assumed to apply to the linear regime, presumably because they are mostly expressed in terms of parameters suited to straightforward frequency response analysis techniques. The few requirements specifically associated with full amplitude control inputs, which would certainly invoke any actuation and aerodynamic non-linearities, are typically open loop time response requirements such as roll performance, and would not necessarily illustrate any PIO tendency. Nevertheless there is no general exclusion of large amplitude and non-linear conditions from consideration, and indeed "*the effects of the control equipment should not be overlooked*" in calculations or analyses directed towards investigation of compliance with the specifications.

The realm of the safety-related high order PIO

The following is a brief resume of the author's successful experience in high order PIO solution and subsequent elimination by design over the period from 1976 up to the present, extracted mostly from Reference 3.

At the time of the 1976 Tornado landing PIO, there were no criteria or appropriate data generally available to explain it. However, it had clearly grown out of the stick pumping in the landing flare, an activity described by Bihrle in 1966. He noted that just before touchdown, pilots would often engage in a rapid pitch control oscillation in phase with pitch acceleration, at frequencies well above the short period. The acceleration amplitude was consistently around ±6.5 deg/sec_. Bihrle concluded that pilots acted this way to generate confidence in pitch control as the speed reduced towards the stall when very precise flight path control was needed for a smooth and safe landing. The activity was also quite subconscious, all pilots being unaware of it.

The author had used the stick pumping theory in the Tornado design process to ensure that there was adequate hydraulic pump flow capacity at idle engine rpm in the landing approach, and in fact found in flight records that pilots did stick pump as predicted. However, the Tornado pitch attitude dynamics differed significantly from previous conventional aircraft. These consistently feature stick pumping at typically 8 to 10 rad/sec resulting in an attitude oscillation that is very small. The amplitude is usually less than a fifth of a degree peak to peak and is effectively unnoticeable. The Tornado stick pumping frequency was about 3 to 4 rad/sec. and at the nominal acceleration level the attitude would be around 2 degrees peak to peak. Some pilots used larger pumping amplitudes than others. The likely trigger seemed to be that the pilot suddenly became aware of the attitude oscillation, and was presented unexpectedly with a ready-made PIO situation with the attitude already 180 degrees out of phase.

Stick pumping does not trigger PIO in conventional aircraft. The obvious solution at the time was to ensure that the attitude dynamics in the stick pumping frequency region were made to favour the subconscious pitch acceleration pumping activity, and not to encourage the possibility of the unstable pilot-attitude PIO coupling which occurs at similar frequencies. The "synchronous pilot" PIO model proposed by Ashkenas and McRuer around 1964, expressed as a gain element and assumed to apply control in anti-phase to the attitude oscillation, was clearly evident in the Tornado PIO. With no pilot phase contribution, the closed loop instability naturally occurred at the frequency where the aircraft attitude phase lag to control inputs was around 180 degrees. The author concentrated studies on the aircraft dynamics in this region.

Figure 3 shows the calculated Tornado landing case pitch attitude frequency responses for four different pitch control law configurations. The unaugmented mode was rather sluggish but was otherwise perfectly acceptable. It had already become clear that the stick command gain at low speeds in the first augmented version, which experienced the PIO, was too high as it was excessively easy to saturate the pitch control system. The large amplitude ratio at the 180° phase lag frequency meant that large oscillations could easily be generated by quite moderate stick inputs. In the complete absence of any other criterion whatever, the policy was adopted that a stability margin must remain if any pilot again used the same gain as in the accident.

The second control law version, which was nearly in a flight cleared status at the time of the accident, had already halved the PIO response gain at low speeds with its substantial reduction in stick command gain, and was approved for use. The author expressed reservations because the linear dynamic characteristics of the second version were little changed from the first version. The sensation pilots had of having to "feel for the ground" in the first version was caused by a marked lag in the onset of pitch acceleration in the time response, which was much larger than in the unaugmented case where conventional actuator dynamics were the only high order effect. In the second version the transient acceleration lag had been scarcely reduced at all, and some pilots still found a slight imprecision at touchdown. The author's concern was eventually justified by an incipient non-divergent PIO, distinguished in the flight record mainly by the pilot's statement that he had sensed its onset. As the tailplanes were close to their nominal rate limit, the effective safety margin was unacceptably small. Further use of full augmentation for take off and landing was again prohibited until a final solution was developed.

The third version followed the author's embryonic ideas about the importance of the attitude dynamics around the 180 degree phase lag frequency. It further reduced the PIO gain and the transient acceleration lag by speed-dependent scheduling of the lag-lead stick command pre-filter to a unity gain at low speed. The lag-lead was restored at higher speeds and was later redesigned for pitch tracking optimisation. This version has successfully prevented a recurrence of landing PIO since its introduction more than twenty years ago.

Criteria evolution

The concept of the synchronous pure gain pilot model became a powerful tool in the discovery of solutions to high order PIO and design criteria to prevent it. Though the pilot actions were later found to vary from the pure attitude-related gain model, often with highly non-linear behaviour, the fundamental pilot actions are always tightly synchronised to components of the attitude response. The policy of dealing with safety-related PIO as a specifically localised problem of attitude dynamics complete in itself, separately from considerations of general handling qualities, has proved to be correct and has led to the author's successful design criteria.

The availability after 1978 of the LAHOS data, Reference 5, enabled the development of the preliminary design criterion discussed in Reference 4. This was based on the nominal stick pumping amplitude and the attenuation of the attitude response between the frequencies at 120 degrees (the author's own early version of bandwidth) and 180 degrees phase lag. The first factor is directly related to the PIO frequency at 180 degrees lag, and favours a high frequency value. The second factor was a gain margin of a sort, but did not explicitly define the absolute PIO gain. The Jaguar FBW demonstrator, designed to this and other "Gibson criteria", began flight tests in 1981 with a high degree of confidence that this PIO problem would not occur, justified in the event as it never did. This may have been the first aircraft control system specifically designed to prevent PIO from the outset.

Continued analysis of the LAHOS data resulted in a more coherent and readily identifiable set of parameters enabling a positive approach to elimination of PIO by design. Figure 4 (from a 1986 paper and given in Reference 3) shows the essential differences between "low order-like"responses with no safety-related PIO tendency and "high order-like" responses with severe PIO tendencies. Note that these terms are not usefully related to the actual order of the flight control system. The most severe LAHOS PIO examples were generated by the addition of a single lag pre-filter to conventional dynamics, while it is perfectly possible for a 60th order FCS to show a low order-like response in the critical PIO region. Design criteria based on these observations utilised the phase rate (similar to phase delay but localised to the 180 degree lag PIO frequency) and the PIO frequency as shown in the figure, with a maximum permitted PIO gain of one sixth of a degree per pound of stick force. These criteria, used in the design of the EAP demonstrator, gave even greater confidence that the PIO problem was defeated. This was again justified by its extremely successful 1986 to 1991 flight program in which no PIO occurred.

These criteria were incorporated the formal handling qualities specification for the Eurofighter, which is showing all the excellent handling qualities of the closely related EAP. The design needs of the fixed gain control mode that was used for a small number of initial flights made it necessary to identify handling limits that were acceptable and safe rather than excellent, since naturally this mode could not be optimised for all speeds, especially at touch down. This resulted in further analysis by the author in 1993 of the LAHOS data to identify PIO gain limits to better quantify Level 2 and Level 3 PIO effects, and the phase rate metric was modified to the average phase rate (exactly the same as phase delay but expressed in different units) as a more accurate measure of high order lag effects. These are shown in Figure 5. (Despite the limitations of the fixed gain mode, the approach and landing qualities were still very satisfactory).

Some interpretation is necessary in the meaning of the gain limits, as it can be the case that a response might be classed as Level 2 by its phase rate and frequency, but as Level 1 or Level 3 by the gain criterion. The author would interpret the gain as signifying better or worse PIO characteristics, so that any oscillation would be unlikely to diverge with a Level 1 gain but would probably be divergent with a Level 3 gain. The response should still be classed as Level 2 in the first case but must be downgraded to Level 3 in the second case.

The author's adoption of "Level" boundaries in design criteria carries no official status, but reflects only his own analysis of the experimental data based on pilot comments and ratings according to the "Level" concept.

Applicability of Figure 5

The criteria boundaries represent an analysis of a range of response dynamics that is relatively small compared with the numbers of PIO events that have actually occurred. Many of the configurations were flown only once by only one pilot, and the opinion rating attached to it might not be repeated exactly by other pilots. Other configurations might have led eventually to a PIO given enough exposure to more pilots and more difficult flight conditions. There is a considerable "grey area" in deciding whether an oscillation should be called a PIO or pilot over-control resulting from unfamiliarity or insufficient adaptation. It is unlikely that exact boundaries of Level 1, Level 2 and Level 3 PIO qualities could ever be precisely delineated for all examples of high order PIO.

With three different parameters to be assessed, one of them potentially requiring some interpretation, it cannot be claimed that this criteria set is guaranteed to quantify with absolute accuracy the pilot rating of the PIO tendencies of past configurations. What is certain is that the further outside the Level 1 limit boundaries that the response of a new design penetrates, the worse its PIO tendencies will be. On the other hand, responses just within the Level 1 limits in all respects are unlikely to experience significant high order PIO, but they still possess undesirable residual high order characteristics. The classical aircraft of old without power control actuation would plot far out of sight to the right on the bottom edge of the phase rate figure, with a response gain equally far out of sight downwards on the gain plot. Between this ideal extreme and the practical reality lies a range of increasing high order effects that will eventually lead to PIO tendencies. Except for unavoidable actuation dynamics, these effects are entirely artefacts of, and therefore under the control of, the control law designer.

It will be recalled that the definition of Level 1 includes the Cooper-Harper 3 pilot rating with "some mildly unpleasant deficiencies". A good designer should not simply be content to obtain the minimum standard just within the Level 1 limits. The designer should set handling qualities aims equivalent to CHR 2, or better still, CHR 1 which is "*excellent, highly desirable*". The concept of an optimum design aim for handling qualities designated Level 1* (Level 1 star) was used in the EAP control law design guidelines. By illustrating factors that have been associated with PIO ranging from severe to mild or none at all, the Figure 5 criteria point to the response dynamics to be avoided by the maximum possible margin to ensure the absence of PIO.

The following Level 1* limits were recommended for linear response design:

- Maximum average phase rate of 50 deg/Hz, equal to a phase delay of 0·07 seconds.
- Minimum attitude PIO frequency of 1·0 Hz.
- Maximum attitude to stick force gain of -20 dB or 0·1 deg/lb at the PIO frequency.
- Maximum attitude acceleration lag of 0·18 seconds in the time response.

(These numbers apply for typical combat aircraft and control inceptors. For other types such as transport aircraft, similar principles but different numbers may be expected.)

Figure 6 revisits the Tornado configurations, which were rectified without benefit of any proven criteria, to compare them with the final version in Figure 5. It supports the author's inference that the first and second pre-filter configurations were not sufficiently different dynamically. The reliance placed at the time on improving the PIO gain value as a major factor in the solution is confirmed by the gain criterion which correctly indicates their relative handling. Although the production version did resolve the PIO problem, it would not pass the later design processes which led to Level 1* anti-PIO qualities in the EAP for example.

Figure 7 compares the stick pumping at touchdown of the Tornado second pre-filter version in the incipient PIO incident and the EAP on an early flight touchdown. The sloppy, low frequency and large amplitude pumping of the Tornado with about ±10 lbs of stick force and ±1_ inches of stick input compares dramatically with the classically rapid, small amplitude pumping of the EAP with about 2 lbs of stick force and ±_ inch stick input, both cases close to the expected frequencies and producing slightly more than the Bihrle value of pitch acceleration. The high degree of control that can be exercised by designers over this crucial area of pilot activity is thus clearly demonstrated.

Accounting for actuator saturation

Although the Tornado landing PIO diverged into the non-linear regime of actuator rate limiting, it was resolved by linear control law modifications. During later development of the "bolt on" incidence limiting system, actuator non-linearity became a major issue. Linear analysis in the design stage showed some acceptable reduction in phase margins from the healthy 55 degrees of the CSAS, and simulation, non-linear modelling and rig tests cleared the system for flight. After some 40 flights, a very large amplitude self-sustaining oscillation occurred at about 300 knots.

A quasi-linear actuator response model was derived from matching rig tests. Figure 8 shows the very rapid loss of phase once full rate saturation commenced, typical af acceleration limiting (Reference 6). This was used to calculate the aircraft attitude dynamics shown in Figure 8. The dominant feature is the "explosive" growth in the PIO gain as the control inputs become larger. As the actuator demand doubles from ±7·5 degrees of tailplane to ±15 degrees, the amplitude ratio quadruples giving eight times the response for twice the stick input. A new non-linear model of the actuator was also developed with an excellent match to the rig results for all demand amplitudes. With this model the event could be replicated exactly by analysis. This enabled the correct design modifications to be developed which effectively linearised the large amplitude response dynamics, not merely by reducing the phase lag due to rate saturation but by virtually preventing the occurrence of the saturation altogether.

The most significant factor was found to be the actuator acceleration limiting. The oscillation event could not be replicated analytically using only the actuator rate limit. This is not usually discussed in the literature, but it is obvious that the pure saw-tooth waveform often presented as actuator rate limiting cannot occur in practice. The finite time it takes for the main control valve to be moved from one end to the other of its stroke represents the acceleration limit. The Tornado tail actuator control valves were driven by an integrated quadruplex actuator, and though fast it adversely affected the saturated large amplitude response dynamics. While most fly by wire actuators have servo drives with much higher bandwidth and rate, the effect of the acceleration limit is always present and must be included in the actuator modelling for any serious design analysis of large amplitude PIO resistance.

However, the best means of preventing problems is to provide sufficiently high rates and to ensure that the forward path command gain at higher frequencies is not unnecessarily large. If the linear design is also sufficiently low order-like, then the dynamics at the PIO frequency may change gradually as the input amplitude increases but will not show any sudden and large changes to trigger a PIO.

Ideally, the rates would be chosen to ensure that the actuation remains unsaturated at frequencies up to the PIO value using the maximum possible pilot inceptor amplitude. The use of design inputs smaller than this ignores PIO history. Unfortunately the rates will probably need to be chosen before the control law design is sufficiently developed to ensure this at critical flight conditions. A rate sufficient to reach full deflection from neutral in 0·2 seconds permits a full cycle of maximum amplitude oscillatory control travel while fully rate saturated in 0·8 seconds (i.e. 1·25 Hz) if there is no serious acceleration limiting. It is hard to imagine that this would not be sufficient when coupled with proper demand attenuation at PIO frequencies. For lower rates this attenuation can be adjusted to suit.

The choice of desirable maximum rates can be confused by misunderstanding the implication of the units of rate. High numbers tend to alarm management. The important parameter is how long it takes for a control to be applied. If a minimum time of 0·2 seconds is desired, the corresponding rate for roll control by a differential tailplane system of ±5 degrees authority is 25 deg/sec (although this would be inadequate for the tailplane's symmetrical pitch control function with perhaps a total travel of ±15 degrees). For a spoiler system with 50 degrees deflection, the equivalent rate is 250 deg/sec. Allowing for the differing control surface sizes and hinge moments, the hydraulic power requirements would be roughly similar despite the 10 to 1 range of angular rates. It is important to get over the message that high rate capability does not mean that pilots will sit there thrashing the controls at maximum rate for long periods, therefore requiring large hydraulic power and flow capability. It is only necessary to provide sufficient accumulator capacity to allow one or two large transient inputs followed by a short dwell in which time the accumulator can be recharged. It is lack of transient rate capability that can lead a pilot into a saturated PIO.

Such a provision has been made on the Jaguar FBW, EAP and Eurofighter with actuator rates of up to 100 degrees per second. Because of their high instability levels, these aircraft could not tolerate significant rate saturation in the pitch controls. The rudder control rate was also critical, since its heavy usage to minimise sideslip in providing "feet off" co-ordinated rolling can require high rates to prevent loss of control in carefree gross combat manoeuvres involving full pitch and roll inputs in any combination including simultaneously. A second line of defence is to place software rate limits of a lesser value on the actuator inputs, e.g. 80 degrees per second, so that the actuators never reach a hard limit. A third defence is to place software rate limits on the inceptor output signals so that the actuator input rate limits are not invoked or at least are invoked only very briefly. Inceptor signal rate limiting, being series or open loop, has been found to be tolerated more readily than closed loop saturation at the actuators. None of these aircraft has shown the slightest tendency to Type 2 or Type 3 saturation effects in flight.

Designing and testing for good handling

While the thrust of this paper has been the prevention of safety-related PIO, it goes without saying that the provision of good handling qualities is a necessary precursor. This includes the prevention of pitch oversensitivity and non-safety-related "low order" PIO such as pitch bobble or the "PIO syndrome" effect due to excessive attitude dropback or an excessive Bode plot shelf width. These can easily be dealt with by use of the methodologies described in Reference 3, for example. Again the designer should aim for "Level 1*" qualities, so that inevitable shortfalls in some areas will still provide Level 1 handling. Generally this aim can be achieved by a K/s-like behaviour below the bandwidth frequency, but this must be applied to the appropriate response.

Although control of an aircraft invokes both attitude and flight path, excellent results have been obtained by optimising the attitude and accepting the fall-out flight path response. This can be taken only so far, however. The latter may well acquire non-classical features such as "g creep" and this must always be assessed for acceptability. Flight path control must take precedence in the landing task, for example, where path control PIO is always a possibility even with classical response dynamics. Here it is also possible to apply the desired K/s-like dynamics to the HUD in the form of a quickened climb-dive or velocity vector symbol, giving very precise flight path predictability and touch down control.

Generally, the faster and higher an aircraft flies, the more dominant the control of flight path becomes. More strictly, it is control of angle of attack rather than pitch rate that becomes more important. This is because the steady pitch rate in manoeuvres becomes small relative to the angle of attack required, which takes too long to acquire initially at anything like the steady pitch rate value. Substantial pitch rate overshoot and attitude dropback ratios then become necessary. An extreme example, discussed (with very approximate data) in Reference 3, is the YF-12 in cruise at Mach 3 or about one kilometre per second, and hence with extremely low pitch rates per g. Figure 9 shows a time response sketch indicating a good K/s-like path response but an attitude dropback ratio of 5 and pitch rate overshoot ratio of 6, which are very large by normal standards.

Although such attitude parameters would be highly unsatisfactory in the majority of normal flight conditions, here their effects are rather insignificant. The normal acceleration increment of about 0·11g used to acquire an attitude change of 0·3 degrees for a 1000 foot per minute climb in a height change manoeuvre required a steady pitch rate of only about 0·07 degrees per second. Hence the physical dropback and peak pitch rate were about 0·35 degrees and 0·4 degrees per second. A K/s-like attitude response could be enforced, say by a lag-lead command prefilter, but the result would be an impossibly long hang-off or g creep as shown in the second sketch. Despite excellent attitude control, the flight path angle response is made so sluggish that a slow overdriving PIO would be the most likely outcome of any attempt to acquire a constant altitude or climb angle. Whether this is truly safety-related is not clear, but it would certainly give a supersonic airliner captain a hard time with hand flying.

By the start of pre-flight clearance testing, all traces of serious PIO should have been removed by rigorous design and analysis employing up to maximum amplitude inputs as noted earlier. Even though this may not represent normal realistic control usage (though it is normal for truly carefree handling aircraft, where anything goes), a control system unable to withstand this has not been properly designed. A piloted simulation search for PIO triggers may well be carried out, but failure to find a trigger task may only mean that the right one has not been thought of. A PIO will always occur, eventually, if the response dynamics permit it. PIO cannot occur if it has been designed out of the system, a possibility that has been demonstrated now on several fly by wire aircraft. A fixed base simulation is certainly capable of showing that Type 2 or Type 3 PIO characteristics are not present, provided that the control system dynamics are very accurately modelled from theoretical analysis and rig tests.

After the Tornado, flight testing for PIO at Warton has been confined to a few high pilot gain precision tasks. One was synthetic HUD target tracking, which showed up a small lateral tracking oscillation on the EAP caused by a feature introduced to optimise rapid turn entry co-ordination. On the Jaguar FBW, flight refuelling trials were done at the end of its programme in its most unstable configuration, without specific pre-task tests but with knowledge of excellent formation qualities and absolute confidence by then in its freedom from PIO. Eight dry contacts were made showing very easy control. On Eurofighter, tests of very close formation flying were made behind a Tornado prior to actual contacts with a Victor tanker. The refuelling task was found to be an order of magnitude easier than with previous conventional aircraft, and in fact Cooper/Harper ratings of 1 and 2 were given. Very aggressive pitch tracking has shown an extremely stable tracking platform. Flight testing for safety-related landing PIO has not been seen as either practical or necessary given the intense scrutiny applied to the design and pre-flight testing.

Final comments

To design a control system and only then to test it for PIO is a very high risk strategy. To ensure freedom from PIO, it is essential to plan its absence from the very beginning, starting with a properly constructed and thought out control law layout, maintaining a highly visible block diagram on which all paths can be followed and their effects understood, and considering the impact on possible PIO of the system hardware and of every change to the control laws.

Reference 7, an excellent review of the past PIO problem initiated after the YF-22 PIO in 1992, recommends a change in paradigm from "Proceed unless a PIO problem is proven to exist" to

"Proceed only when resistance to PIO is proven". It will be obvious that this author whole-heartedly concurs.

The essence of safety-related PIO prevention by design is simply stated: the PIO frequency cannot be too high, the PIO gain cannot be too low, the phase delay cannot be too small, and the large amplitude response cannot be linearised too much.

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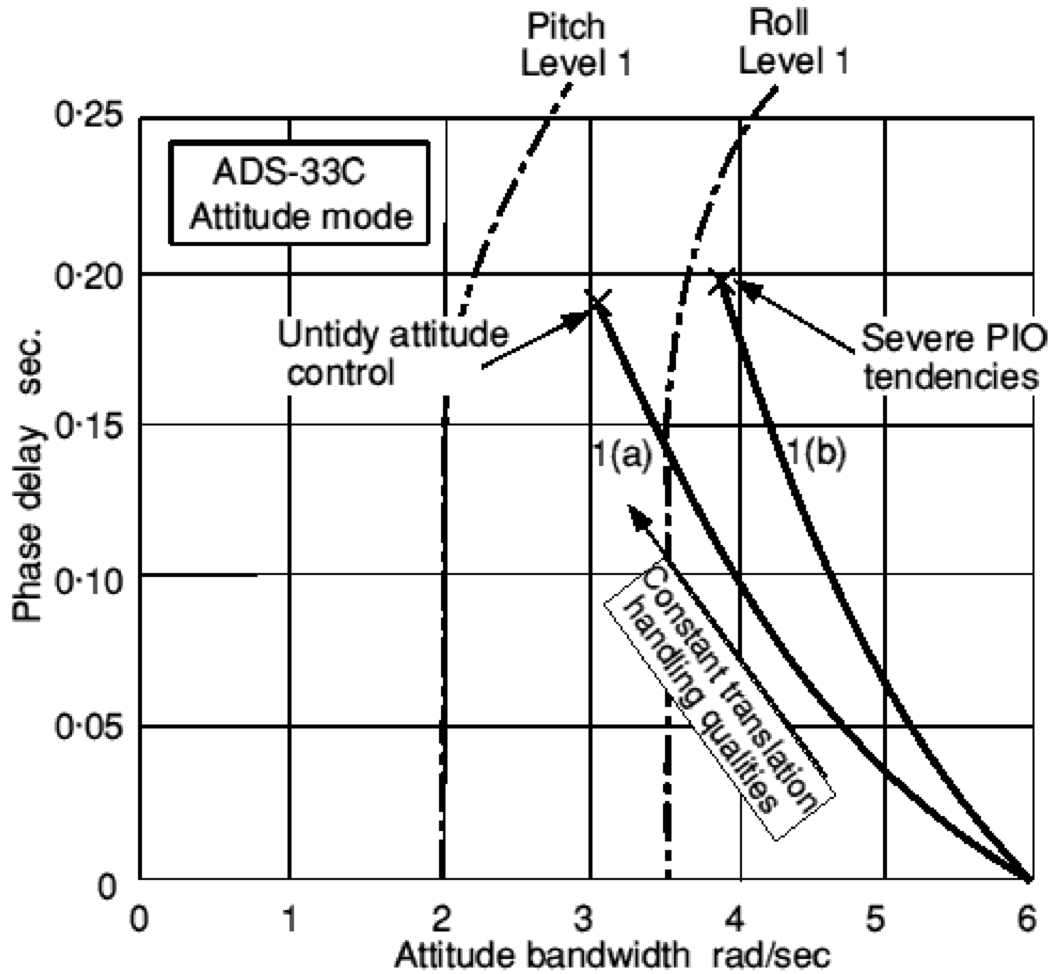


1(a) has critical damping and low PIO gain, with translation control qualities that remain constant as bandwidth reduces and phase delay increases, while the attitude control becomes untidy.

1(b) has Level 1 damping (0·5), phase delay and bandwidth to ADS-33C, but degrades to dangerous PIO due to high PIO gain and motion coupling as phase delay increases.

Figure 1 Generic ASTOVL research:
Lateral translation handling in roll attitude mode

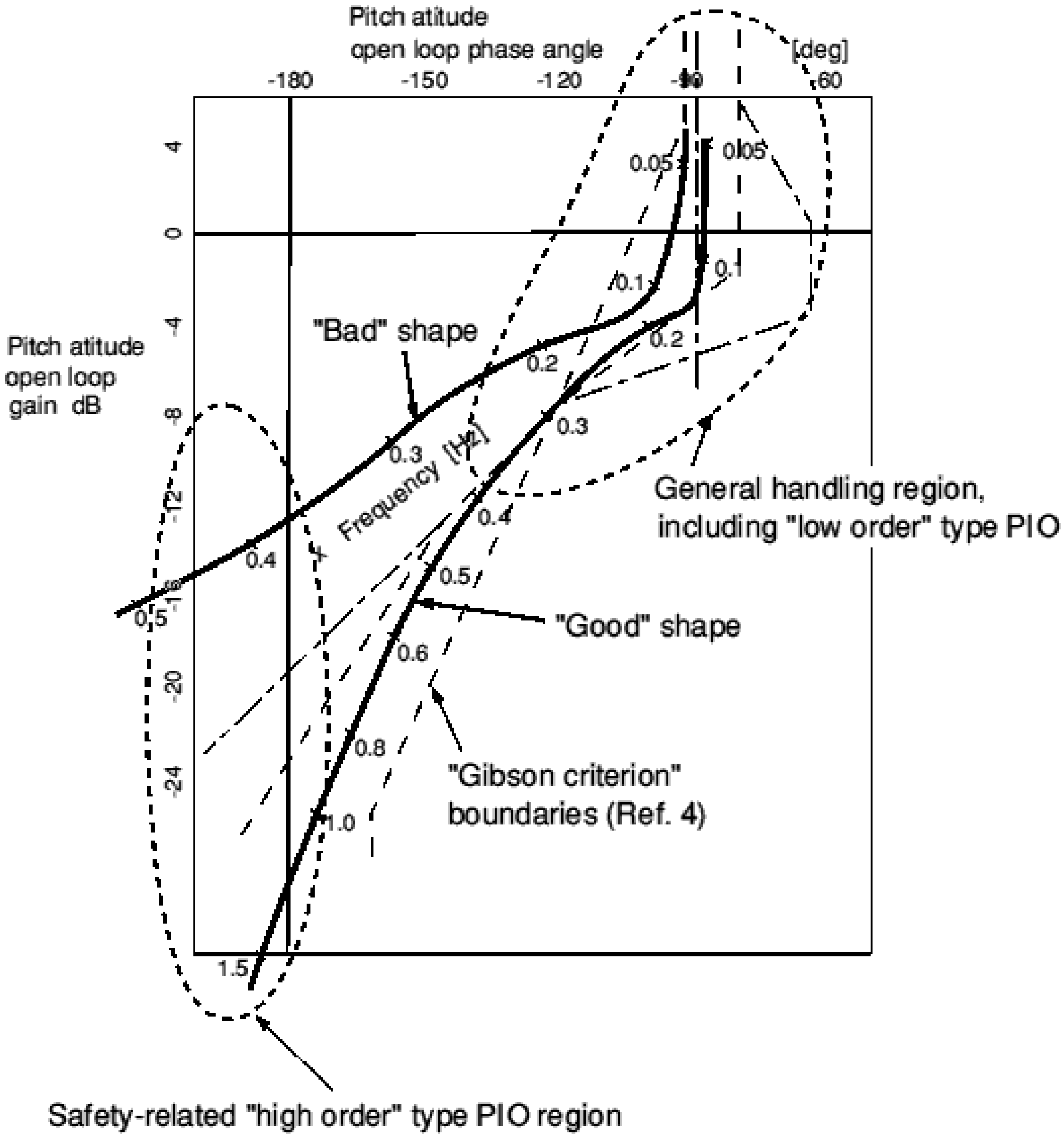
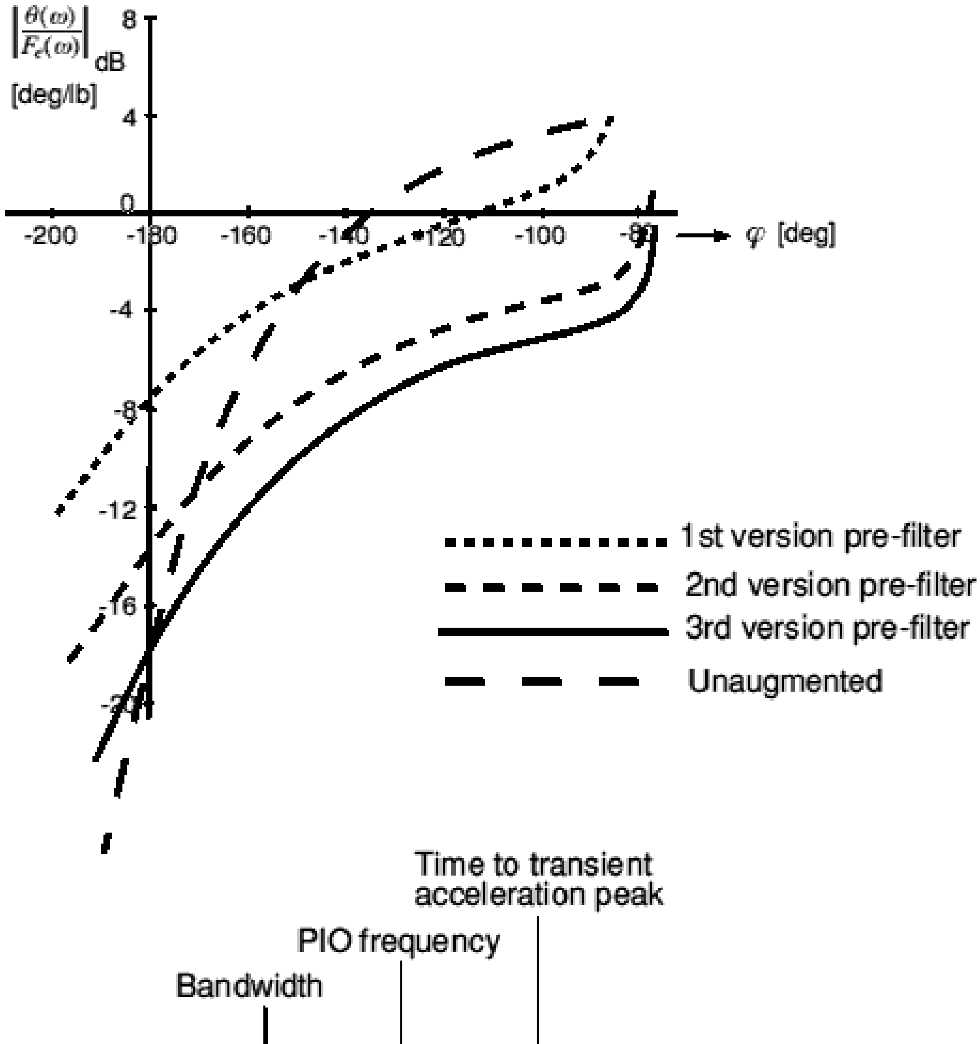


Figure 2 Frequency response qualities illustrated by non-parametric shape



Version	$\omega_{(-120)}$ Hz	$\omega_{(-180)}$ Hz	$t_{\dot{q}}$ sec	Pre-filter characteristics
1st	0·245	0·43	0·35	(1 + 0·157s)/(1 + 0·47s)
2nd	0·245	0·455	0·3	(1 + 0·133s)/(1 + 0·454s)(1 + 0·0625s)
3rd	0·26	0·535	0·22	(1·0)
Unaug.	0·145	0·44	0·12	(1·0)

Figure 3 Tornado pitch attitude responses at landing: solution to PIO by development of the command pre-filter.

The unaugmented and third version pre-filtered dynamics are PIO-free.

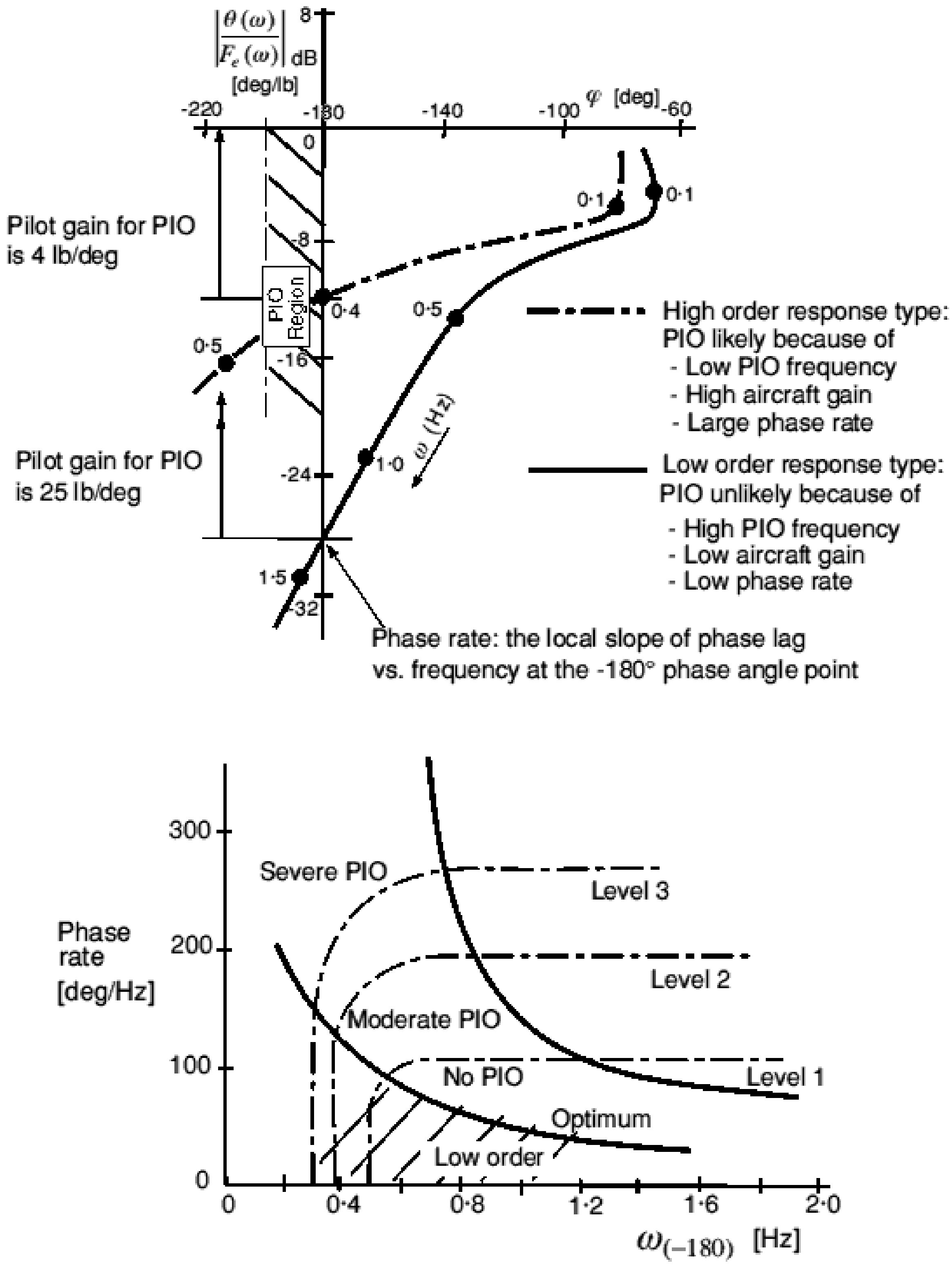


Figure 4 PIO tendency indicators and design guidelines derived from LAHOS etc.

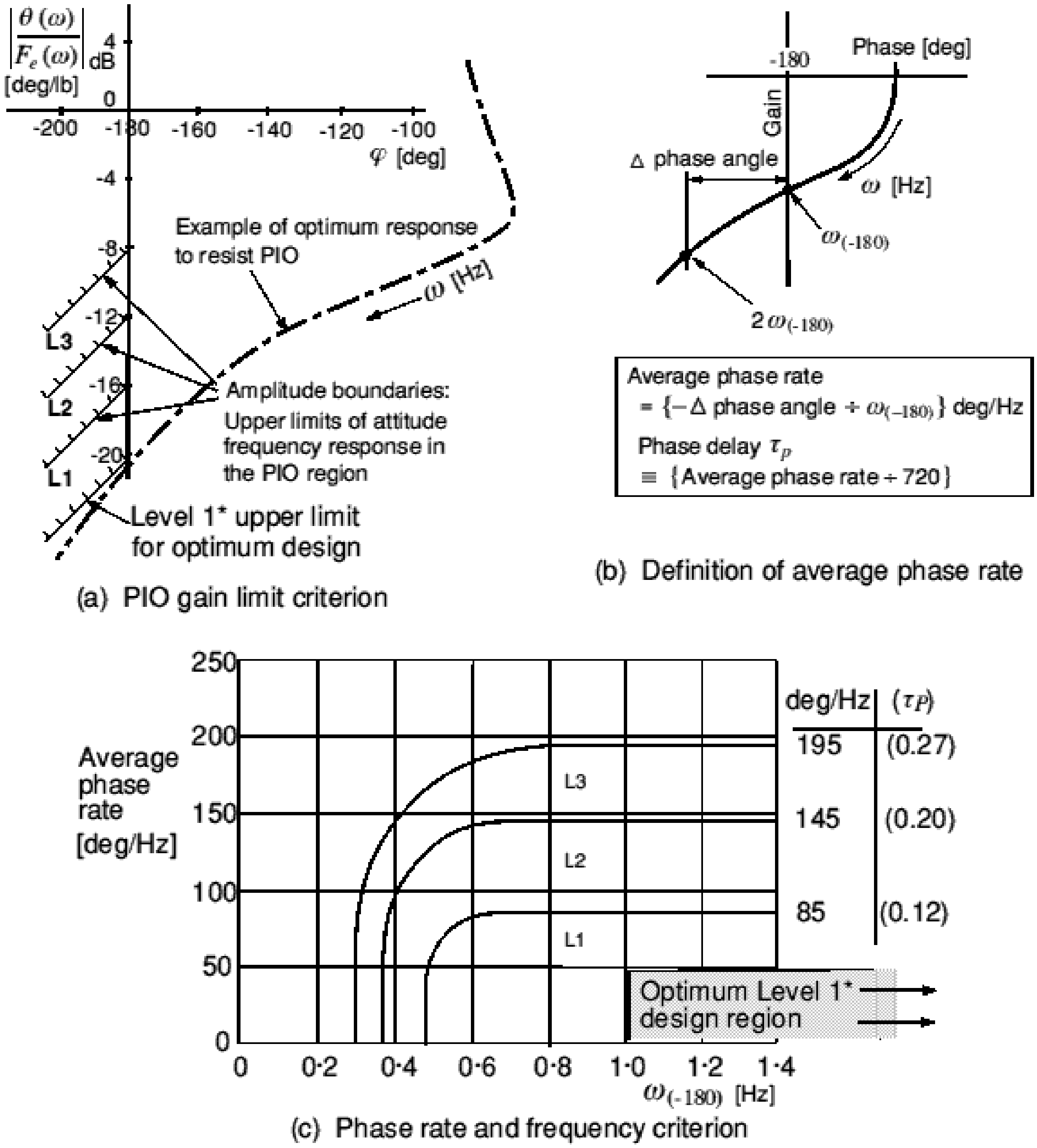
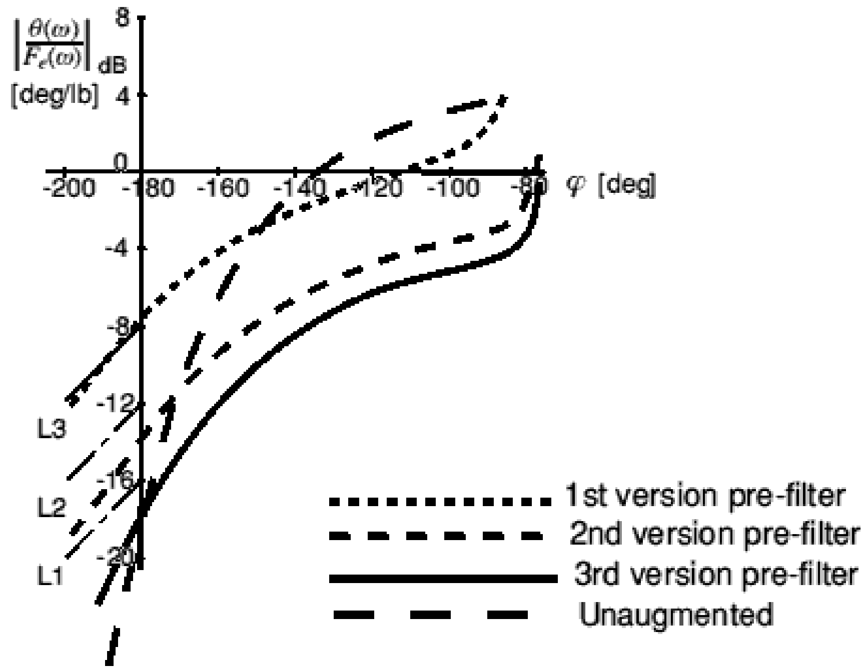


Figure 5 Final development of PIO criteria (1993)

1. Level 1, 2 and 3 boundaries represent historical data.
2. Undesirable residual high order characteristics exist within the Level 1 region near the low frequency boundary limit.
3. Best design practice for freedom from linear high order PIO requires the more stringent Level 1* gain, phase rate and frequency limits.



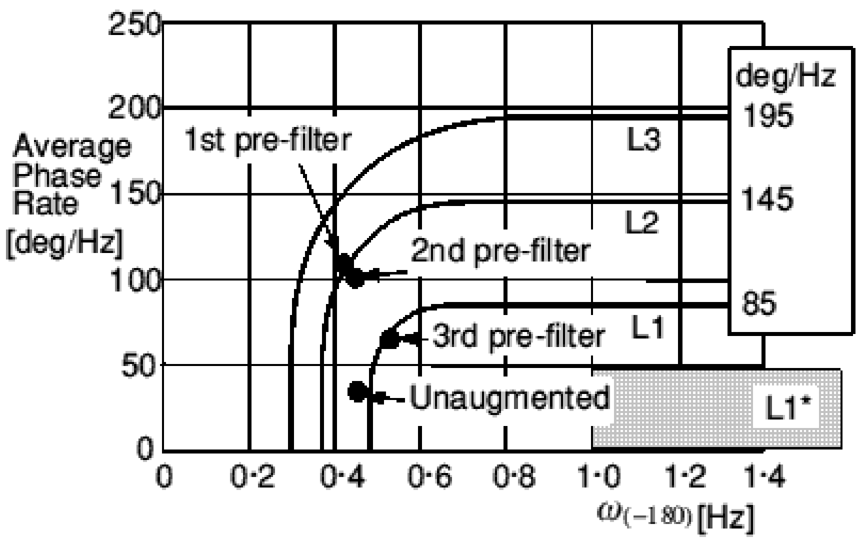


Figure 6 Tornado viewed in retrospect against author's later criteria

Note: although the 3rd pre-filter just satisfies the criterion and has prevented PIO for 20 years, it would not have been accepted as a new design by subsequent criteria.

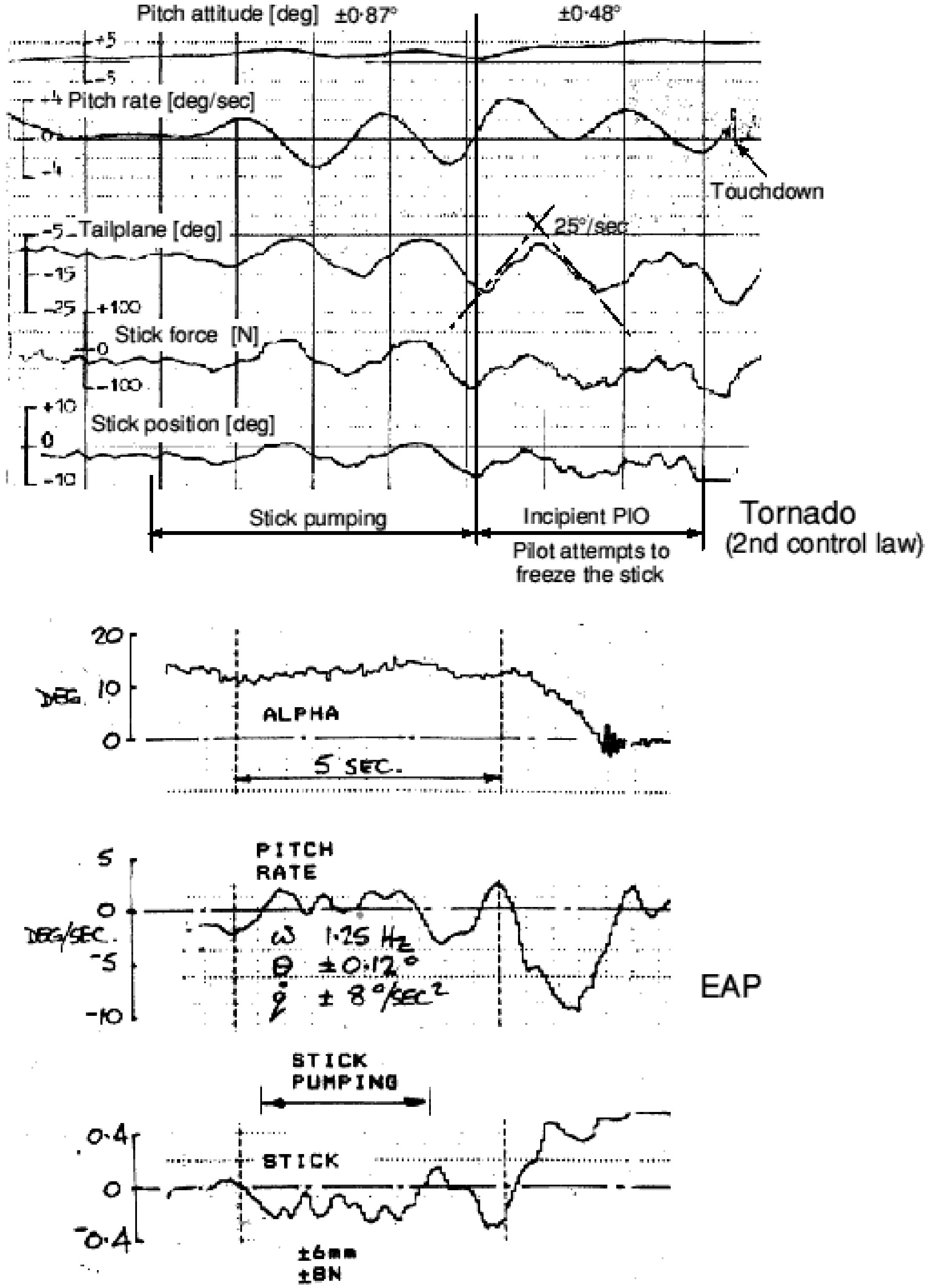


Figure 7 Effect of design process on stick pumping and associated PIO resistance

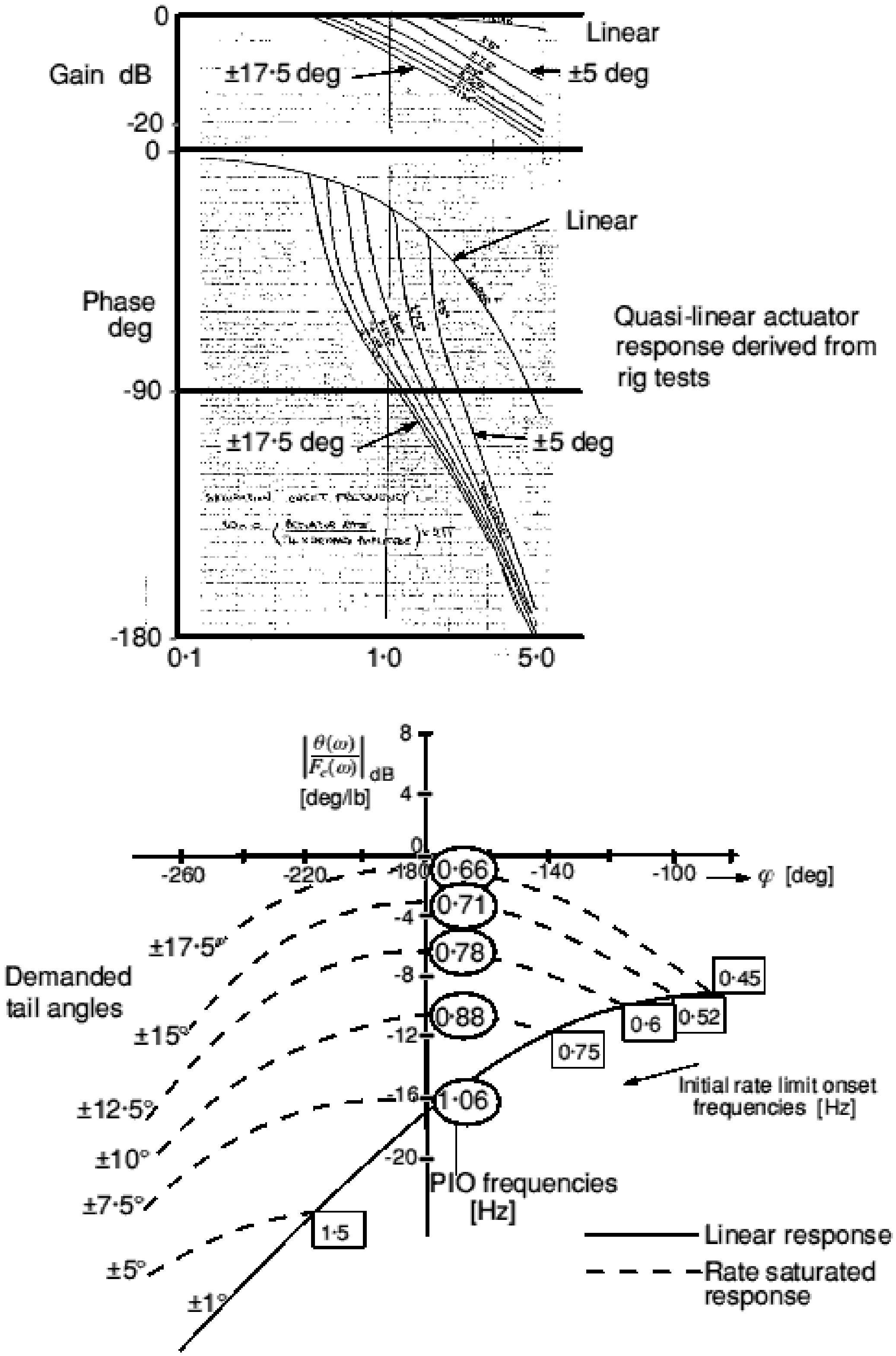
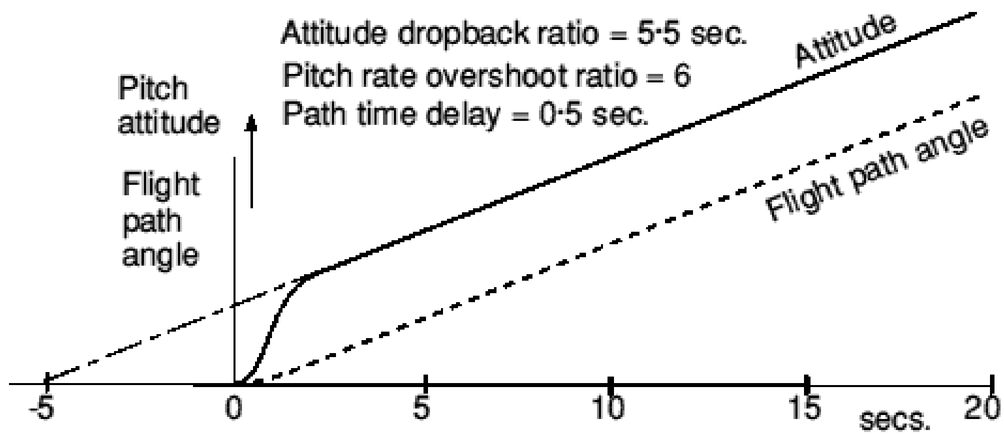
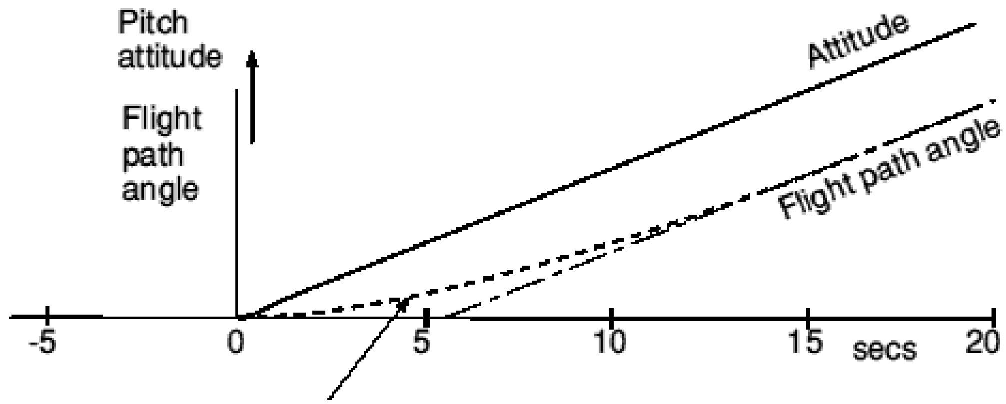


Figure 8 Significant non-linear actuation effects on PIO characteristics



Nominal YF-12 time response
at Mach 3 cruise



Short period roughly approximated by:

$$\omega_{sp} = 0{\cdot}5 \text{ rad/sec}$$

$$\zeta_{sp} = 1{\cdot}3$$

Path delay = 5·2 sec.

$$\text{YF-12 with pre-filter} = \frac{1 + 0{\cdot}8s}{1 + 5{\cdot}5s}$$

Figure 9 Sluggish PIO-prone flight path response caused by inappropriate pitch attitude optimisation

98-4333

PILOT-INDUCED OSCILLATION PREDICTION WITH THREE LEVELS OF SIMULATION MOTION DISPLACEMENT

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Abstract

Simulator motion platform characteristics were examined to determine if the amount of motion affects pilot-induced oscillation (PIO) prediction. Five test pilots evaluated how susceptible 18 different sets of pitch dynamics were to PIOs with three different levels of simulation motion platform displacement: large, small, and none. The pitch dynamics were those of a previous in-flight experiment, some of which elicited PIOs. These in-flight results served as truth data for the simulation. As such, the in-flight experiment was replicated as much as possible. Objective and subjective data were collected and analyzed. With large motion, PIO and handling qualities ratings matched the flight data more closely than did small motion or no motion. Also, regardless of the aircraft dynamics, large motion increased pilot confidence in assigning handling qualities ratings, reduced safety pilot trips, and lowered touchdown velocities. While both large and small motion provided a pitch rate cue of high fidelity, only large motion presented the pilot with a high fidelity vertical acceleration cue.

Notation

a,b,c	prefilter zeros and poles, rad/sec
a_{model}	model acceleration, ft/sec^2, rad/sec^2
a_{motion}	motion system commanded acceleration, ft/sec^2, rad/sec^2
F(x,y)	variance ratio with x and y degrees of freedom
$F_{lon}, F_{lat}, F_{ped}$	long., lateral stick and pedal force, lbs
$\dot{h}_{td}$	touchdown vertical velocity, ft/sec
K	control system prefilter gain
K_{mot}	motion system filter high-freq gain
K_θ	control system gearing, deg/in
$L_{\delta lat}$	lateral control sensitivity, 1/sec^2/in
$M_{\delta e}$	elevator control sensitivity, 1/sec^2
$N_{\delta lat}$	directional control sensitivity, 1/sec^2/in
n	number of points in each mean
p	probability that effects are random
s	Laplace transform variable, rad/sec
$T_{\theta 1}, T_{\theta 2}$	pitch-to-elevator zero time constants, sec
β	sideslip angle, deg
δ_e	elevator deflection, deg
δ_{ec}	commanded elevator, deg
δ_{ecfilt}	filtered commanded elevator, deg
δ_{estick}	commanded elevator from stick, deg
$\delta_{lon}, \delta_{lat}, \delta_{ped}$	longitudinal, lateral stick and pedal deflection, in
ζ_{dr}	Dutch roll damping ratio
ζ_{mot}	motion filter damping ratio
ζ_p, ζ_{sp}	phugoid and short period damping ratio
ζ_1, ζ_2	control system prefilter damping ratios
ζ_ϕ	complex zero damping ratio in bank-to-aileron transfer function
θ, ϕ	pitch and roll angles, deg
τ_r, τ_s	roll and spiral mode time constants, sec
ω_{dr}	Dutch roll natural frequency, rad/sec
ω_{mot}	motion system filter natural frequency rad/sec
ω_p, ω_{sp}	phugoid and short period natural fr rad/sec

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ω_1, ω_2 control system prefilter natural frequencies, rad/sec

ω_ϕ complex zero natural freq. in bank-to-aileron transfer function, rad/sec

Introduction

Ground simulation has not been very successful at predicting subsequent in-flight pilot-induced oscillations (PIOs). A recent study recommended that "validating simulation details, protocols, and tasks and collecting and correlating them with flight test results should be given high priority" to improve this simulation weakness.[1]

With two fixed-base simulators of different capabilities, Ref. 2 evaluated the longitudinal PIO tendencies of configurations tested in a PIO flight test study.[3] The simulation results followed the general trend of the in-flight data; however, the worst in-flight configurations were not as severe on either fixed-base simulator.

The purpose of this study was to determine what effect simulator platform motion has on predicting PIOs. Here, three simulator platform motion characteristics were examined: large, small, and no motion. Five pilots flew a landing task with 18 different sets of longitudinal dynamics with each motion configuration. Both pilot-vehicle performance and subjective data were taken and compared with the previous in-flight study.[3]

Apparatus and Tests

Task

The in-flight task was replicated as much as possible.[3] Pilots started at 135 knots and 1.5 nmi from the runway and flew three visual approaches to full touchdown with each configuration. One approach was straight-in, and one each started with a 150-ft left or right lateral offset from the touchdown point. During the approach, pilots were instructed to maintain constant speed and remain on the glidepath (–2.5 degs) and localizer. Deviations were indicated on head-down instruments. At the start of the run, the aircraft was placed 1/2 dot off the desired localizer and glideslope.

For the left and right offsets, pilots held that offset until an automated voice instructed the pilot to "correct." The pilot then maneuvered the aircraft to land on the desired touchdown point. The "correct" command occurred when the runway overrun disappeared from the visual field-of-view, which corresponded to an altitude of 100 ft.

Figure 1 shows the desired touchdown point, which was the near-left corner of the 1000-ft fixed distance marker located to the right of centerline. This desired touchdown point matched the flight-test study. Table 1 gives the performance standards for the task.

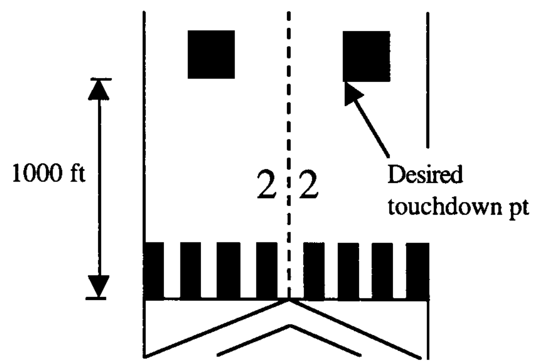

Figure 1 – Landing task

Table 1 – Task performance standards

	Desired	Adequate
PIOs	None	None
Longitudinal touchdown error	+/– 250 ft	+/– 500 ft
Lateral touchdown error	+/– 5 ft	+/– 25 ft
Approach airspeed	+/– 5 kts	–5/+10 kts

Math model

Longitudinal configurations. A linear stability derivative model[4] generated the aerodynamic forces and moments on the aircraft. Bare airframe derivatives were combined from several sources.[3,5,6] Response feedbacks of angle-of-attack and pitch rate to the elevator were used to simulate the different pitch configurations, given below, which mimics the NT-33 variable stability aircraft.[5] Figure 2 shows the dynamic blocks of the pitch axis dynamics.

The simulation centerstick dynamics were measured as:

$$\frac{\delta_{lon}}{F_{lon}}(s) = \frac{0.125(22^2)}{s^2 + 2(0.7)(22)s + 22^2}$$

These dynamics are slower than the 25 rad/sec stick longitudinal natural frequency stated in Refs. 3 and 7 due to force-feel system limitations of this simulator cockpit. The ergonomics of the stick matched Ref. 7.

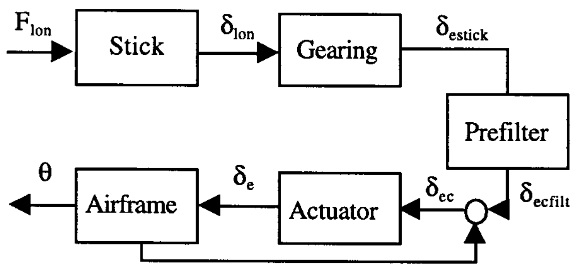

Figure 2 – Longitudinal block diagram

Fourteen prefilters were simulated as in the in-flight experiment. These prefilters consisted of first, second, and fourth-order linear filters. These filters are of the form below, and Table 2 gives their values:

$$\frac{\delta_{e_{cfilt}}}{\delta_{e_{stick}}}(s) = \frac{K(s+a)}{s+b}$$

$$\frac{\delta_{e_{cfilt}}}{\delta_{e_{stick}}}(s) = \frac{K}{s+c}$$

$$\frac{\delta_{e_{cfilt}}}{\delta_{e_{stick}}}(s) = \frac{K}{s^2+2\zeta_1\omega_1 s+\omega_1^2}$$

$$\frac{\delta_{e_{cfilt}}}{\delta_{e_{stick}}}(s) = \frac{K}{(s^2+2\zeta_1\omega_1 s+\omega_1^2)(s^2+2\zeta_2\omega_2 s+\omega_2^2)}$$

Table 2 – Control system prefilters

Filter	K	a	b	c	ζ_1	ω_1	ζ_2	ω_2
B	3.0	3.3	10	–	–	–	–	–
D	0.5	20	10	–	–	–	–	–
1	1.0	–	–	–	–	–	–	–
2	10	–	–	10	–	–	–	–
3	4.0	–	–	4	–	–	–	–
5	1.0	–	–	1	–	–	–	–
6	16^2	–	–	–	0.7	16	–	–
7	12^2	–	–	–	0.7	12	–	–
8	9^2	–	–	–	0.7	9	–	–
9	6^2	–	–	–	0.7	6	–	–
10	4^2	–	–	–	0.7	4	–	–
11	16^4	–	–	–	0.93	16	0.38	16
12	2^2	–	–	–	0.7	2	–	–
13	3^2	–	–	–	0.7	3	–	–

Commanded elevator deflection was the sum of the prefilter output and the feedbacks of angle-of-attack and pitch rate. The elevator actuator dynamics were modeled as a second-order filter with the NT-33 rate and position limits.[7] In the linear range, the actuator dynamics are:

$$\frac{\delta_e}{\delta_{e_c}}(s) = \frac{75^2}{s^2+2(0.7)(75)s+75^2}$$

Four sets of aircraft dynamics were evaluated. The differences among the dynamics were effectively in the short-period mode. The pitch-to-elevator transfer function had the following form:

$$\frac{\theta}{\delta_e}(s) = \frac{M_{\delta_e}(s+1/T_{\theta_1})(s+1/T_{\theta_2})}{(s^2+2\zeta_p\omega_p s+\omega_p^2)(s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2)}$$

Table 3 gives the parameters for the above transfer function. For all configurations, $M_{\delta e}$=–3.3 1/sec^2.

Table 3 – Aircraft dynamics

A/C	$T_{\theta 1}$	$T_{\theta 2}$	ζ_p	ω_p	ζ_{sp}	ω_{sp}
2	12	1.4	0.15	0.17	0.64	2.4
3	12	1.4	0.17	0.16	1.0	4.1
4	12	1.4	0.16	0.16	0.74	3.0
5	12	1.4	0.16	0.15	0.68	1.7

The remaining parameter to be specified is the gearing between the elevator command from the stick and the longitudinal stick position. For the 18 tested configurations, which represent combinations of the aircraft dynamics and prefilters, the gearings are listed in Table 4. As an example, for configuration 2-B, the "2" corresponds to the values in Table 3 and the "B" corresponds to the values in Table 2.

Subsequent to the experiment's start, information from the Ref. 2 authors indicated that the Table 4 gearings may have been 70% higher than in the flight test. To evaluate the effect of different gearings on the results, a mini-experiment was run using the Ref. 2 gearings with configurations 3-1, 3-D, and 3-12. Differences between gearings were less than or equal to one handling qualities and pilot-induced oscillation point.

Each of the 18 configurations was verified by performing frequency sweeps on each and overplotting the result against the analytical pitch-rate-to-stick-deflection transfer functions.

Table 4 - Gearings

Config	K_θ	Config	K_θ
2-B	-2.94	3-8	-7.29
2-1	-2.94	3-12	-7.29
2-5	-4.33	3-13	-7.29
2-7	-2.94	4-1	-3.46
2-8	-2.94	4-2	-3.46
3-D	-8.65	5-1	-1.73
3-1	-7.29	5-9	-1.73
3-3	-7.29	5-10	-1.73
3-6	-7.29	5-11	-1.73

The engine model consisted of a first-order transfer function from throttle input to thrust output. The time constant was nonlinear and depended on RPM.[7]

Lateral. Using a lateral-directional stability derivative model, coefficients were adjusted to achieve the following modal and sensitivity characteristics:

$$\tau_r = 0.3 \text{ sec}$$

$$\tau_s = 75 \text{ sec}$$

$$\omega_{dr} = \omega_\phi = 1.3 \text{ rad/sec}$$

$$\zeta_{dr} = \zeta_\phi = 0.2$$

$$\left|\frac{\phi}{\beta}\right|_{dr} = 1.5$$

$$L_{\delta_{lat}} = 0.7 \text{ rad/sec}^2\text{/in}$$

$$N_{\delta_{ped}} = -0.2 \text{ rad/sec}^2\text{/in}$$

These characteristics were also verified with frequency sweeps.

Atmosphere. Dryden turbulence with rms magnitudes of 3 ft/sec was used. A vertical 1-cosine gust occurred when the aircraft reached an altitude of 100 ft. The gust had a peak of 12 ft/sec and was time scaled based on the 6.7 ft chord of the NT-33.

Safety pilot. Evaluation pilots in the NT-33 flight study were accompanied by a safety pilot, who ended the evaluation and assumed control of the aircraft if a potentially hazardous situation occurred. If a safety pilot assumes control, then questions arise immediately on that configuration's "controllability" from the handling qualities point of view. The presence of a safety pilot can also add a factor of stress, since another set of eyes is watching the evaluation pilot.

In this simulation, an automatic safety pilot was implemented that assumed control of the simulated model when the nosewheel's vertical speed exceeded –8 ft/sec below a center-of-mass height of 12 feet. This criterion was developed empirically and was well received by the pilots. Upon activation, the pilot's controls went dead, a voice said "my airplane," and the math model initiated a go-around.

Simulator

Motion system. The NASA Ames Vertical Motion Simulator (VMS) was used.[8] It is the world's largest-displacement flight simulator, with capabilities shown in Figure 3. The cockpit was oriented for large longitudinal travel. The dynamics of the motion system were measured during the experiment using frequency response testing techniques.[9] These dynamics were fit with an equivalent time delay in each axis. Software feedforward filters were used to tune the delays to achieve a close match among axes. The equivalent time delays for the surge, sway, pitch, roll, and yaw axes were all 80 msecs, and the heave axis had 110 msec of delay. By comparison, delays in the NT-33 model following control system have been suggested as being in the 45-60 msec range.

VMS Nominal operational motion limits

Axis	Displ	Velocity	Accel
Vertical	± 30	16	24
Longitudinal	± 20	8	16
Lateral	± 4	4	10
Roll	± 18	40	115
Pitch	± 18	40	115
Yaw	± 24	46	115

All numbers, units ft, deg, sec

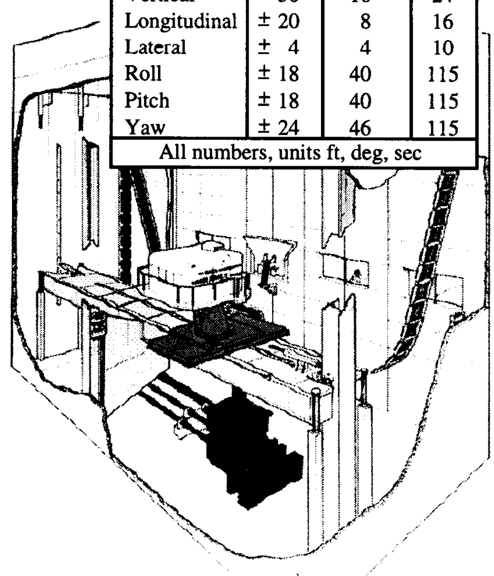

Figure 3 – NASA Ames Vertical Motion Simulator

Visual system. The visual scene was rendered with an Evans & Sutherland ESIG-3000 image generator. Three monitors comprised the field of view, as shown in Fig. 4. The visual system had a measured time delay of 80 msec from the pilot's stick position to the visual scene. Figure 5 shows the visual scene with the aircraft near the runway. The nose of the simulated aircraft is at the bottom of the field-of-view. Window mullions were added (oval in Figure 5) to replicate the cockpit.[7]

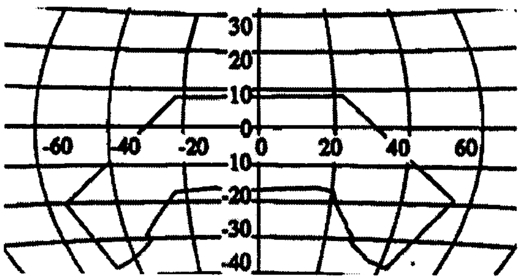

Figure 4 – Cockpit field-of-view

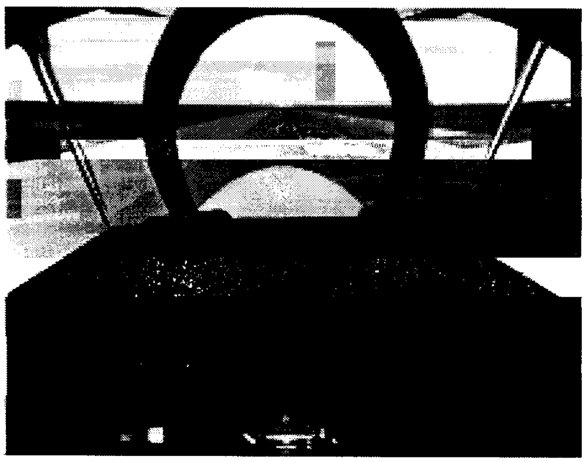

Figure 5 – Simulator cockpit photo

Cockpit. The lateral stick and pedal dynamics were measured as:

$$\frac{\delta_{lat}}{F_{lat}}(s) = \frac{0.25(16^2)}{s^2 + 2(0.7)(16)s + 16^2}$$

$$\frac{\delta_{ped}}{F_{ped}}(s) = \frac{0.0167(25^2)}{s^2 + 2(0.7)(25)s + 25^2}$$

A head-up display was video mixed with the visual scene. The display included a pitch ladder, altitude above sea level, airspeed, rate-of-climb, heading, range, and a flightpath marker. The flightpath marker represented center-of-mass flightpath and used raw data only.

Motion configurations

Three motion configurations were examined: large, small, and no motion. The VMS motion platform software was modified to implement each.

Large motion. The classical washout motion control laws of the VMS were used for this configuration. Second-order high-pass (washout) filters exist between the math model accelerations and the commanded motion system accelerations. These filters have the form:

$$\frac{a_{motion}}{a_{model}}(s) = \frac{K_{mot}s^2}{s^2 + 2\zeta_{mot}\omega_{mot}s + \omega_{mot}^2}$$

In each of the six motion degrees-of-freedom, both K_{mot} and ω_{mot} were adjusted to keep the motion system within its displacement limits using motion system fidelity criteria suggested initially by Sinacori[10] and revised and validated subsequently.[11] Table 5 shows the values used. The damping ratio, ζ_{mot}, was 0.7. In addition to these cues, roll/sway coordination and residual tilt crossfeeds were present in the motion logic.[12]

Table 5 - Large motion system parameters

Axis	K_{mot}	ω_{mot}
Pitch	1.00	0.20
Roll	0.40	0.50
Yaw	0.65	0.20
Longitudinal	0.65	0.40
Lateral	0.50	0.50
Vertical	0.80	0.30

Small motion. A coordinated-adaptive algorithm, used on many of today's hexapods, was employed in the small motion configuration.[13,14] This algorithm assumed a mathematical model of a hexapod platform with 60-in stroke actuators. Thus, the stroke limiting that occurs when commanding several axes was present. Euler angles and translational positions of the platform were back solved on line from the resulting (and potentially limited) actuator positions.[15] The Euler angles and positions were then used to drive the VMS platform.

Second-order high-pass filters were used in the translational axes, while the rotational axes used a first-order high-pass filter (unlike the Large motion configuration). The second-order filters had a damping ratio of 0.7, except for the surge axis, which was 0.8. For comparison, Table 6 gives the gains and natural frequencies (or pole locations) for the small motion filters. The gains listed are the maximum values, as the coordinated-adaptive algorithm reduces these values when the actuators near their travel limits. These gains were adjusted to use as much of the 60-in actuator stroke as possible.

Table 6 – Small motion system parameters

Axis	K_{mot}	ω_{mot} (or pole)
Pitch	0.50	0.30 (pole)
Roll	0.25	0.81 (pole)
Yaw	0.70	0.30 (pole)
Longitudinal	0.11	0.67
Lateral	0.45	0.90
Vertical	0.13	0.90

No motion. The motion system was turned off in this configuration.

Comparison with fidelity criteria. Figure 6 plots each axis of the large and small motion configurations against the validated criteria of Ref. 11. These points are determined by finding the magnitude and phase of the respective motion filter evaluated at 1 rad/sec.

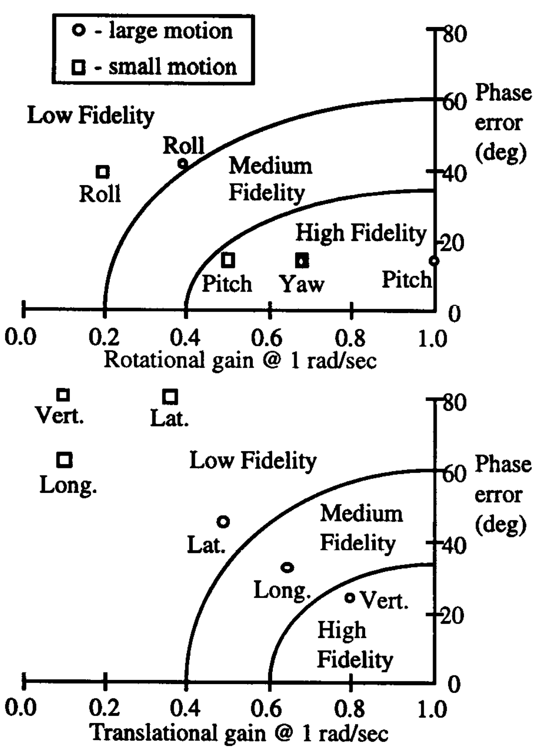

Figure 6 – Motion fidelity prediction

In the rotational axes, high motion fidelity is predicted for both pitch and yaw motion with the large and small motion configuration. Roll motion is low fidelity in both motion configurations, since the roll axis was attenuated to minimize the false lateral specific force cueing during coordinated rolling maneuvers.

In the translational axes, all of the small motion cues are predicted to be low fidelity. For large motion, the fidelity improves, especially for the vertical axis, which provides a key cue for this task. This figure shows the benefit of large motion in fidelity terms.

Pilots

Five experience test pilots, hereafter referred to as A-E, participated. Pilot A was an FAA test pilot, pilots B-D were NASA Ames test pilots, and pilot E was a Boeing test pilot.

Experimental procedure

Summarizing the experimental variables, they were:

1. motion configuration (3),
2. aircraft configuration (18)

Thus, each pilot evaluated 54 configurations. Pilots A, B, and E evaluated each configuration at least twice. Pilots C and D evaluated each configuration only once.

The pilots each read the same experimental briefing. They had no knowledge of the configurations, which were randomized. After flying the task, the pilots were told of their performance. Then, they assigned a handling qualities rating using the Cooper-Harper scale,[16] a Pilot Confidence Factor,[16] and a Pilot Induced Oscillation Rating (PIOR).[6]

Results and Discussion

Objective data

Example PIO. Figure 7 illustrates a classic divergent PIO that occurred with Pilot B, configuration 3-12, and large motion. The pilot was nearly on the longitudinal stick stops. The pilot gave this configuration a Cooper-Harper rating of 8, and a PIO rating of 5. PIOs of this severity and for this extended period of time did not occur for either the small or no motion configurations.

The average frequency of the PIO in Figure 7 is 3.0 rad/sec (the average in-flight PIO frequency of this configuration was 2.2 rad/sec). Also shown on the pitch rate and normal acceleration traces are the motions that both the large and small motion configurations would produce for this visual motion.

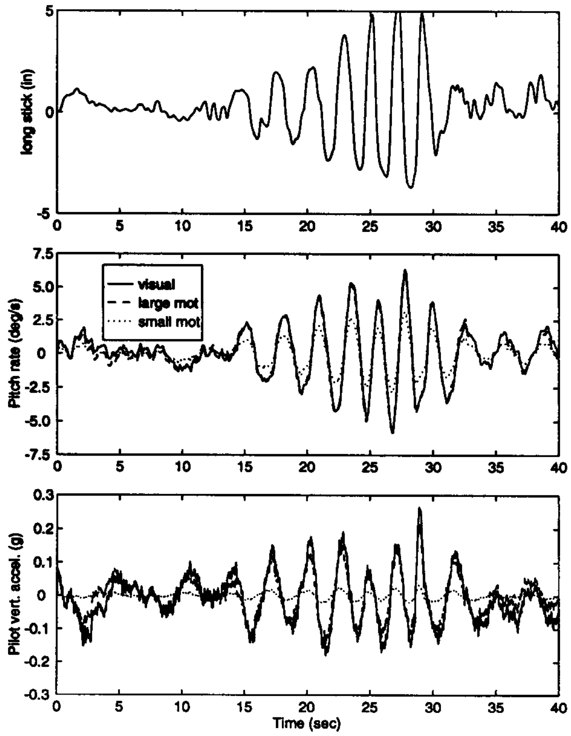

Figure 7 – Example PIO

At the PIO frequency, the large motion configuration provides 100% of the pitch rate cue, and it leads the visual scene by only 5 degs of phase angle. So, the dashed line overlays the solid line. These values may be determined by inserting 3 rad/sec into the motion system filter discussed earlier with the pitch axis parameters (Table 5). The small motion configuration, at best, provides 50% of the visual pitch rate and leads the visual by 6 degs. By motion cueing fidelity standards, both the large and small motion cues are high fidelity.[10,11]

For the normal acceleration, the large motion configuration provides 80% of the visual cue and leads the visual by 3 degs (this value includes the motion filter and the additional 30 msec of delay that the vertical platform lags the visual). But the small motion configuration provides only 13% of the visual cue and leads the visual by 20 degs. By motion cueing fidelity standards, the large motion cue would be high fidelity, and the small motion cue would be low fidelity. It is for this important acceleration cue that large motion provides a simulation benefit, and it is likely the reason for the superior performance of the large motion configuration as discussed later.

Landing performance. Longitudinal touchdown position was analyzed using a two-way repeated measures analysis of variance (ANOVA).[17] While statistically significant differences occurred across the aircraft configurations ($F(17,68)=3.73$, $p<0.001$), differences among the motion configurations were not found ($p>0.2$).

Lateral touchdown position was analyzed, and no significant differences were noted among the aircraft ($p>0.4$) or motion configurations ($p>0.4$). Approach airspeed errors were almost always within the desired performance standard.

During the evaluations, it was noticed that pilots had difficulty in judging sink rate during the flare-to-touchdown as less platform motion was presented. Indications of this fact were either harder landings or the safety pilot assuming control for the small and no motion configurations.

Figure 8 shows the means and standard deviations of vertical touchdown velocities for each motion configuration. Each mean is an average of 90 points (18 configurations x 5 pilots). The ANOVA on these data indicated that the motion configuration affected touchdown velocity independent of the vehicle configuration ($F(2,8)=36.8$, $p<0.001$).[17] Aircraft configuration also affected touchdown velocity independent of motion configuration ($F(17,68)=2.93$, $p<0.001$). No interaction between the motion and vehicle configurations was present ($p>0.3$). Thus, touchdown velocity could be modeled as independent functions of the motion and aircraft configurations:

$$\dot{h}_{td} = f(\text{motion}) + g(\text{aircraft})$$

As more motion was available, pilots were able to lower the touchdown velocity. A previous limited experiment with large motion also indicated this effect when the longitudinal handling qualities were poor;[18] however, the results here indicate that large motion allows lower touchdown velocities regardless of the configuration.

As Table 1 notes, sink rate at touchdown was not a performance parameter in this experiment, which was also the case in the Ref. 3 flight experiment. However, the Ref. 2 simulation experiment added a touchdown performance criterion of $\leq$ 4 ft/sec for desired performance and $\leq$ 8 ft/sec for adequate performance. Had that been the case here, it is expected that even further differences among the motion configurations would have occurred. This is because when more platform motion was added, it compensated for sink rate perception deficiencies in the visual scene.

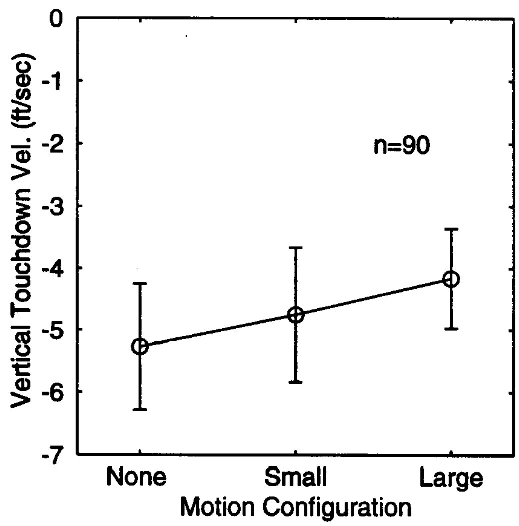

Figure 8 – Touchdown velocities

Safety pilot trips. Figure 9 shows the number of times the automated safety pilot assumed control versus the motion configuration. Over 1400 landings were performed, so the safety pilot assumed control in approximately 10% of the landings. It took control slightly fewer times with small motion than with no motion; however, large motion resulted in significantly fewer safety pilot trips. Many of the safety pilot trips occurred from the inability to judge sink rate.

While it was stated earlier that causing the safety pilot to assume control should raise questions about the configuration's controllability, this seldom occurred. Pilots often felt they were still in control. The issue was that the small or no motion configurations did not assist pilots in their estimation of vertical velocity as did the large motion cues.

Stick activity. Longitudinal stick rms positions were analyzed. Statistical differences occurred across aircraft configurations ($F(17,68)=7.81$, $p<0.001$), with configurations 5-10 and 3-12 having the most activity (0.96 and 0.93 in, respectively). Configurations 2-B and 3-D had the least activity (0.49 and 0.51 in, respectively). No significant differences occurred across the motion configurations ($p>0.1$).

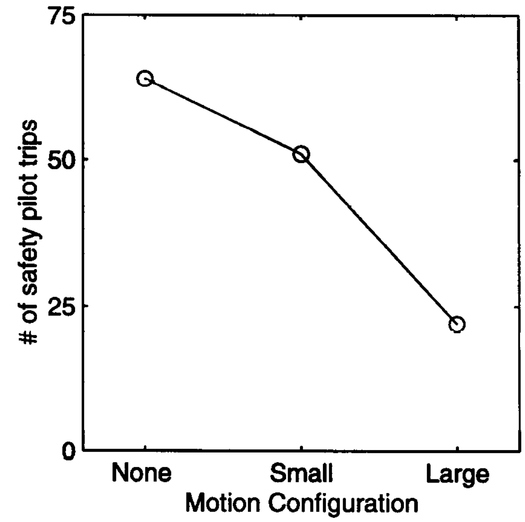

Figure 9 – Safety pilot trips

Handling Qualities Ratings

Large Motion. Figure 10 is a plot of the in-flight HQRs[3] versus the simulation HQRs for the large motion condition. If simulation matched flight, then all points would lie on the diagonal line. A 1-unit HQR band is plotted about this line, which is often taken as the range of an acceptable match. Eight of the 18 configurations lie within this 1-unit band. Very similar trends to that of the Ref. 2 fixed-based simulation are noted. That is, the best configurations in flight were slightly worse in simulation, and the worst configurations in flight were better in simulation.

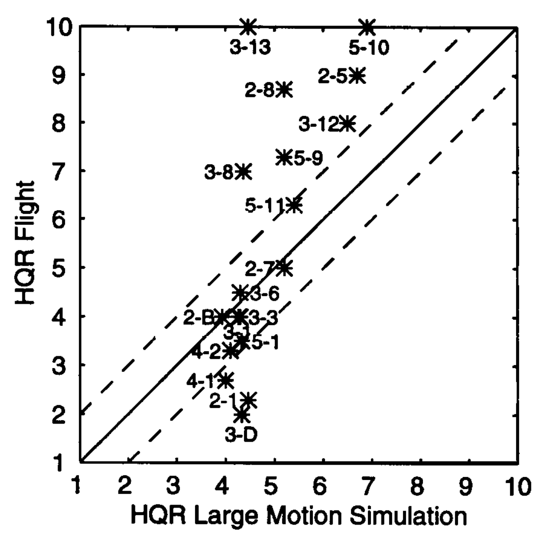

Figure 10 – Flight versus large motion HQRs

Small Motion. Figure 11 shows the in-flight versus simulation HQRs for small motion. Six of the 18 configurations lie within the 1-unit band, which is a degradation from the large motion condition. Again, the same trend on the best and worst configurations existed as for large motion.

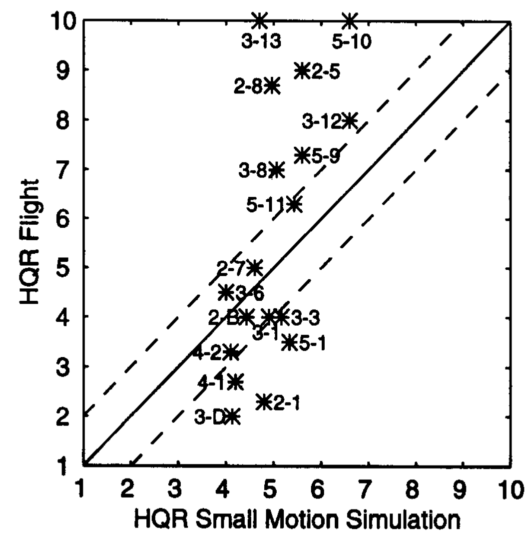

Figure 11 – Flight versus small motion HQRs

No Motion. Figure 12 shows the in-flight versus simulation HQRs for no motion. Five of the 18 configurations were within the 1-unit band, which is a degradation from large motion and small motion. Again, the same trend on the best and worst configurations existed as for large and small motion.

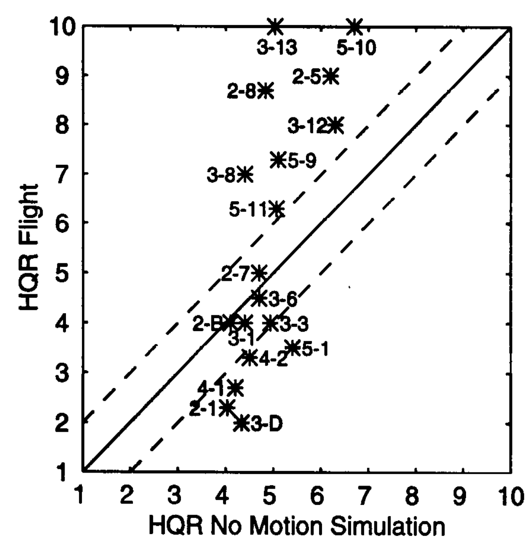

Figure 12 – Flight versus no motion HQRs

Pilot Confidence Factors. Confidence factors of A, B, and C refer to a pilot's opinion that he can assign a handling qualities rating with a high, moderate, or minimum degree of confidence, respectively.[16] Losses of confidence arise when simulation cues are incomplete or inadequate. Figure 13 shows that as more motion is provided, the pilot's confidence in assigning ratings improves. On average, both the no motion and small motion configurations caused the pilot to have less than a moderate degree of confidence in his rating. With large motion, that confidence improved to more than moderate. This difference was statistically significant across the motion configurations ($F(2,8)=5.82$, $p=0.028$). Differences in this measure were not significant across the aircraft configurations ($p>0.1$).

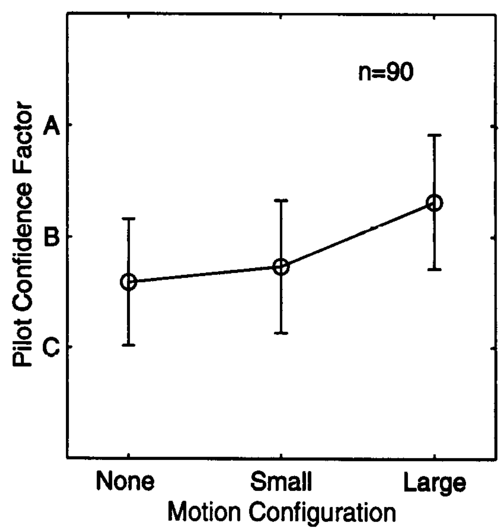

Figure 13 – Pilot confidence factors

PIO Ratings

Large motion. Figure 14 compares pilot-induced oscillation ratings (PIORs) between flight and the large motion simulation. Sixteen of the 18 configurations lie inside the +/– 1 PIOR boundary. Except for four configurations, the in-flight PIORs were, on average, higher than the simulation PIORs.

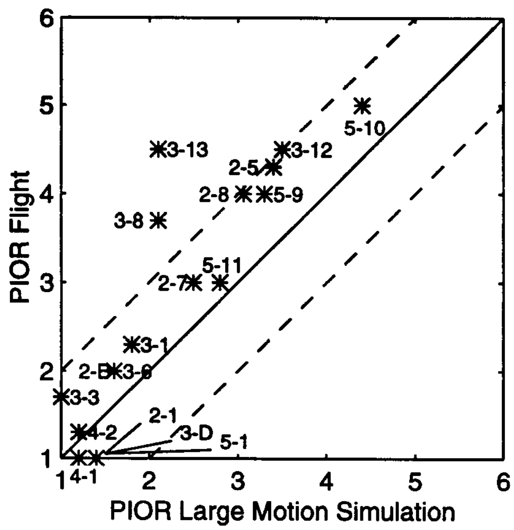

Figure 14 – Flight versus large motion PIORs

Small motion. PIORs for the small motion configuration are shown in Figure 15. Here, 12 configurations were inside the +/– 1 PIOR band, which was the worst performance of the motion configurations. Again, except for four configurations, the in-flight PIORs were worse than the simulator PIORs.

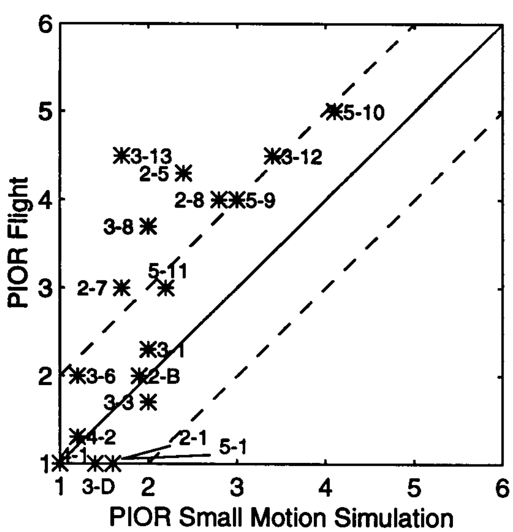

Figure 15 – Flight versus small motion PIORs

No motion. The PIORs for no motion are given in Figure 16. No motion performed slightly better than small motion, but worse than large motion. Fourteen configurations were inside the +/– 1 PIOR band. Still, except for four configurations, the in-flight PIORs were higher than the no motion PIORs.

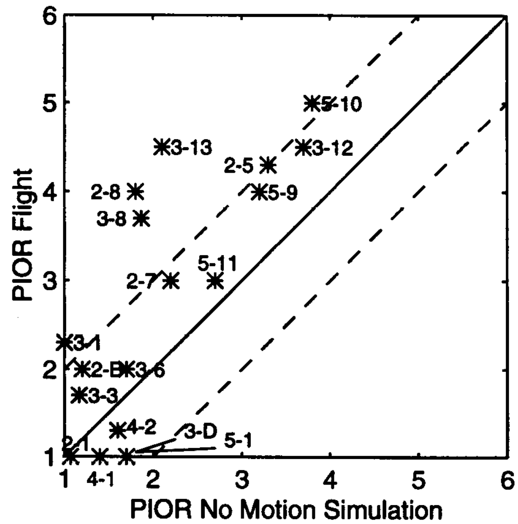

Figure 16 – Flight versus no motion PIORs

Conclusions

A piloted experiment examined the effect of three levels of platform motion displacement on the ability to predict pilot-induced oscillations. Objective and subjective measures were examined for large, small, and no platform motion. The small motion condition represented the displacement of a conventional hexapod platform.

Overall, large motion matched flight more closely than either small or no motion. Specifically, large motion better matched the in-flight pilot-induced oscillation ratings and the handling qualities ratings than did small or no motion. In addition, with large motion, pilots assigned higher confidence factor ratings, achieved lower touchdown velocities, and caused fewer safety pilot trips as compared to the other motion configurations. Finally, only with large motion did markedly divergent pilot-induced oscillations occur.

An example illustrated that high fidelity pitch rate cues were provided by both the large and small motion configurations. However, only large motion allowed high fidelity vertical acceleration cues to be presented. Pilots react strongly to vertical acceleration, and this likely contributed to the large motion configuration providing the best results.

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A Method for the Flight Test Evaluation of PIO Susceptibility

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The handling qualities test method taught at the USAF Test Pilot School is briefly described. This method consists of three parts, or phases: Phase 1 is an evaluation of low bandwidth handling qualities; Phase 2 is an evaluation of high bandwidth handling qualities; and Phase 3 is an evaluation of handling qualities during the operational tasks that make up the design mission of the airplane. Phase 2 high bandwidth testing uses the Handling Qualities During Tracking (HQDT) test technique, which when properly applied has proved remarkably effective in exposing PIO susceptibility in airplanes of every size and shape. For this reason Phase 2 testing is often referred to as a handling qualities "safety gate." If PIO is not experienced during Phase 2 high bandwidth testing, it is unlikely that PIO will be experienced during operational use. If high bandwidth handling qualities are satisfactory, it is unlikely that handling qualities will pose a significant safety of flight concern during operational use.

Introduction The three phase handling qualities test and evaluation method described below has been used at the AFFTC since 1972. When used as described, it has proved remarkably successful as a handling qualities test method and as a means of "optimizing" the flight control system to achieve improved handling qualities. When used in a compromised fashion, it has proved to be correspondingly less successful. The second of the three phases, which centers around high bandwidth Handling Qualities During Tracking (HQDT) testing, has proved especially successful in exposing PIO susceptibility. Unhappily, this valuable tool has often been misunderstood and misapplied, and hence disparaged. Pilots who understand the rationale for high bandwidth HQDT testing, and who have been properly trained in the specialized piloting technique, find it a very effective handling qualities evaluation tool.

Discussion As all of flying qualities testing should be, the three phase handling qualities test method described below is grounded in the model validation test method, which consists of three steps:

1. *Predict the airplane response, based on a model.*
2. *Test the prediction.*
3. *Validate or correct the model, based on the test results.*

The model validation test method is readily recognizable as a form of the scientific method. In Step 1, the handling qualities are *predicted*, using available analytical criteria and piloted simulators. We will not discuss Step 1 in this paper. In Step 2, the airplane handling qualities are *tested* using the three phase test method described below. In Step 3, the handling qualities model is *validated*. We will not discuss Step 3 in this paper. The model validation test method is the most effective, the most efficient, and the safest way to conduct testing. To further emphasize test safety, the handling qualities test method described below is guided by the following procedural rule:

Employ a build-up approach, in which testing progresses from the lowest to the highest level of risk.

To ensure completeness, the handling qualities test method described below is guided by the following principle:

Handling qualities testing should explore the entire spectrum of pilot-vehicle dynamics.

Before proceeding, we pause for two notes.

First, we define handling qualities as the *dynamics, or characteristics, of the pilot plus the airplane*. Second, following the YF-22 PIO incident, we at the Flight Test Center began to refer to PIO as "pilot-in-the-loop" oscillation, rather than "pilot-induced" oscillation. Pilots must be in the loop for a PIO to occur, but pilots do not induce these unwanted oscillations. If anything, it is the airplane that induces them. This is easily shown by noting that the same pilot, flying two different airplanes in the same manner may experience many PIOs in the one but never experience a PIO in the other. When pilots understand that PIO is not their fault, they are more likely to provide objective evaluations, comments, and ratings.

The test method described below is composed of three phases: a low pilot bandwidth phase, a high pilot bandwidth phase, and an operational phase. By "pilot bandwidth" we have in mind both the range of frequencies and the amplitude of control inputs generated by the pilot. "Frequency content" would perhaps be a more descriptive term, but "bandwidth" seems to be more widely used. We will discuss each phase of testing in turn.

Phase 1: Low Bandwidth Testing During Phase 1 testing the pilot conducts an evaluation of low bandwidth handling qualities at safe, up-and-away flight conditions. By low bandwidth handling qualities, we mean the handling qualities characteristics that are associated with relatively smooth (or low frequency), small amplitude pilot inputs. We often refer to Phase 1 testing as "warm-up," or "get acquainted," or "familiarization" testing. Phase 1 low bandwidth testing is designed to introduce the pilot to the airplane under low risk conditions. Phase 1 consists of relatively low bandwidth piloting tasks, including open-loop tasks such as pulse, doublet, and step inputs; semi-closed-loop tasks such as low bandwidth pitch attitude and bank angle captures, steady heading sideslips, and so on; gentle maneuvering in the vicinity of the test airspeed and altitude; and low bandwidth, non-aggressive tracking.

You may object, correctly, that open-loop maneuvers such as pulses, doublets, and steps are not handling qualities test maneuvers at all, because the pilot is not in the loop. We include these maneuvers because they allow the pilot to observe the dynamics, or characteristics, of the *airplane alone* (even though experience shows that an open-loop evaluation may be misleading as an indicator of handling qualities).

Pilots must approach Phase 1 cautiously, even though it is a low bandwidth evaluation. Experience shows that airplanes with less than desirable handling qualities may unexpectedly and quickly draw a pilot into high bandwidth control and PIO. For this reason, pilots must focus on preserving low bandwidth, and be prepared to relinquish control altogether (by freezing or releasing the controls) to arrest an unwanted response such as PIO.

When PIO, or other sufficiently undesirable handling qualities are encountered during Phase 1 low bandwidth testing, strong consideration should be given to correcting these deficiencies before testing progresses to Phase 2 high bandwidth testing.

Phase 2: High Bandwidth Testing During Phase 2 testing the pilot conducts an evaluation of high bandwidth handling qualities. Most of this testing is conducted at safe, up-and-away flight conditions. By high bandwidth handling qualities, we mean the handling qualities characteristics that are associated with aggressive, high frequency, small and large amplitude pilot inputs. Phase 2 consists mainly of HQDT testing. HQDT is perhaps the single most important handling qualities test technique at our disposal, especially when an evaluation of PIO susceptibility is of interest. We often refer to Phase 2 high bandwidth testing as a "safety gate," because experience shows that when this testing is executed correctly and PIO is not exposed, the airplane may be considered PIO-free with near certainty.

There are three principal components of HQDT testing: the piloting technique, the test maneuver, and the pilot evaluation.

The HQDT Piloting Technique The HQDT piloting technique is a simple one. A small precision aim point is selected on a target. This aim point should not be larger than the pipper or aiming index in the gunsight or head-up display. *The evaluation pilot's task is to track the precision aim point as aggressively and as assiduously as possible, always striving to correct even the smallest of tracking errors as quickly as possible.* The effect of this simple technique is to increase the bandwidth of the pilot's control inputs.

A systematic way to fully explore high bandwidth handling qualities is to begin an HQDT maneuver at low bandwidth (that is, using small amplitude, low frequency inputs); then increase the frequency range using small amplitude inputs; then increase the input amplitude while at high frequency. In practice, you will find that this approach works well for airplanes having satisfactory handling qualities, but not as well for airplanes having less than satisfactory handling qualities. The excessive phase lag associated with degraded handling qualities forces a pilot who is attempting to fly with high bandwidth into a coupled pilot-plus-airplane oscillation at a frequency below what the pilot is capable of achieving. These lower frequency coupled oscillations (which may or may not be PIO) are often a valuable indication that the airplane handling qualities are not what you would like them to be. In other words, the inability to achieve high pilot bandwidth, despite a vigorous attempt to do so, may itself be a sign, in some cases, that the airplane handling qualities are less than satisfactory.

Based on the description given in the preceding two paragraphs, experienced pilots will recognize that the HQDT piloting technique is quite different from the low bandwidth "operational" piloting technique used in normal, everyday flying. In normal everyday flying, experienced pilots do not resort to small amplitude, high frequency inputs, and certainly not to large amplitude, high frequency inputs. Instead, they prefer small, smooth inputs deftly applied in an effort to anticipate and correct small errors before they grow into large ones. Consider the operational "guns tracking" task, in which an experienced pilot may initially lead the target, then allow the gunsight pipper to drift back to the target (or allow the target to drift up to the pipper). Instead of aggressively correcting tracking errors, relatively smooth, measured corrections are applied with the goal of "floating" the pipper toward the target. A low bandwidth "operational" piloting technique such as this will improve task performance (especially when the handling qualities are less than satisfactory), but it also hides, or masks, the high bandwidth handling qualities of the airplane. The purpose of the HQDT piloting technique is to bring high bandwidth handling qualities characteristics into the open, where they can be evaluated.

Pilots who are unfamiliar with the purpose of Phase 2 high bandwidth handling qualities testing commonly raise several objections to the specialized HQDT piloting technique. One is that it is "unnatural," or "pilots don't fly that way," or "HQDT might be okay for fighters, but not for big airplanes because no one flys big airplanes aggressively." A second objection is that it results in degraded task performance. A third objection is that "I can make any airplane PIO" or "I can make any airplane look bad" by using the HQDT piloting technique. A fourth objection is that "we're only doing this to pacify the engineers." The first objection is largely, but not entirely true; the second objection is true; and the third and fourth objections are untrue. Let's look at each in turn, briefly.

The first objection, that the HQDT piloting technique is "unnatural" in any airplane and is inappropriate for large airplanes, is largely, but not entirely true. Experience shows that the HQDT piloting technique is not *normally* used by pilots, but is an entirely *natural response* when something happens to elevate a pilot's level of excitement or anxiety above a certain threshold. Also, the natural response of a human pilot to high levels of excitement or anxiety is independent of the size of the airplane. The space shuttle, the C-17, and the B-2 are large airplanes, and each experienced PIOs during testing. The second objection, that the HQDT piloting technique results in degraded task performance, is true. As a practical matter, we observe from operational experience that when excitement or anxiety precipitates a high bandwidth response from a pilot, task performance is degraded. The nature and level of this degraded performance is of interest to us in Phase 2 testing because it is one source of incidents and accidents as well as degraded mission performance. The third objection, which is that "I can make any airplane PIO," or "I can make any airplane look bad" by using the HQDT piloting technique, is false. We show the Test Pilot School students, first using a simulator and then in flight, that a genuinely Level 1 or Level 2 airplane cannot be made to PIO. We show them that a Level 1 airplane will feel crisp and responsive and follow their commands closely even during high bandwidth HQDT testing. They learn by experience that *the HQDT piloting technique will* not *make a good airplane look bad, but it* will *make a bad airplane look bad*. This, in a nutshell, is the purpose of Phase 2 handling qualities evaluation: to expose both the good and bad features of high bandwidth handling qualities. The fourth objection, which is that "we're only doing this to pacify the engineers," is also false. Phase 2 testing, as all of handling qualities testing, is conducted for pilots, not for engineers. It is pilots, not engineers, who must fly the airplane, perform the mission (sometimes under very difficult circumstances that are conducive to high pilot bandwidth), and return safely. It is pilots, not engineers, who must live with the consequences when the test community fails to evaluate the full spectrum of handling qualities, or fails to expose every deficiency, or fails to correct deficiencies when warranted.

An interesting feature of the HQDT piloting technique is that, in most cases, the evaluation pilot is not allowed to use the rudder pedals. This is referred to as "feet-on-the-floor" tracking. At the Flight Test Center, experience has taught us that much can be learned about lateral-directional handling qualities when flying feet-on-the-floor. Pilots are excellent aileron-to-rudder interconnects. When pilots are allowed to use the rudder pedals, they can mask handling qualities deficiencies that might otherwise stand out prominently. However, the HQDT piloting technique should not be thought of as an exclusively feet-on-the-floor technique. There are times when using the rudder pedals is beneficial. For example, the pilot's description of how the rudder pedals were used, together with an analysis of the data, can be helpful in correcting a deficiency.

In HQDT testing the evaluation pilot must not be distracted by the measurement of task performance, such as average tracking error, or time within a given radius of the precision aim point, and so on. Measuring task performance encourages evaluation pilots to abandon or compromise the HQDT piloting technique and reduce their bandwidth. While reduced bandwidth usually results in improved task performance, it also compromises the evaluation of high bandwidth handling qualities. When the HQDT piloting technique is abandoned or compromised, the average test pilot is quite capable of producing good tracking results with a pretty bad airplane. This tells us something about the skills of the pilot, but it doesn't tell us much about high bandwidth handling qualities, which is what we are interested in during Phase 2 testing.

The HQDT piloting technique is not difficult to learn, but it requires practice. The best place to learn and practice this technique is in a flight test simulator. Learning is easier and occurs more rapidly when it is possible to estimate power spectral density functions of the pilot's control inputs immediately after a practice maneuver.

We have noted the importance of large amplitudes and high frequencies in high bandwidth pilot inputs. By "high frequencies" we do not mean that pilots should attempt to track by generating high frequency sinewave inputs. The high frequency component of high bandwidth inputs comes from the *sharpness*, or *quickness* of the pilots inputs. Sharp, quick, control inputs are produced by reacting to tracking errors as rapidly as possible.

We must emphasize the importance of an honest and vigorous effort to use the specialized, high bandwidth, HQDT piloting technique. Otherwise, high bandwidth handling qualities (which are usually the worst handling qualities) will not be fully evaluated during the test program. Instead, these handling qualities will be evaluated in the field, during operational use by line pilots rather than test pilots.

We conclude our brief description of the specialized HQDT piloting technique by remarking again that this technique, which lies at the heart of Phase 2 high bandwidth testing, is often compromised by pilots and engineers who regard it as unnatural and artificially contrived. In fact, however, this technique is entirely natural under certain circumstances. You need only examine time histories of pilot control inputs during a PIO to see that this is so.

<u>HQDT Test Manuevers</u> The heart of high bandwidth handling qualities testing lies in the specialized HQDT piloting technique. Any maneuver that requires the evaluation pilot to use the specialized, high bandwidth, HQDT piloting technique is likely to be a suitable HQDT test maneuver. For this reason there is no exclusive catalog of HQDT maneuvers. Maneuvers that have worked well in the past include constant load factor (or angle of attack) air-to-air tracking maneuvers, wind-up turn tracking maneuvers, tracking while closing on the target, tracking in the power approach configuration (with and without closure), air-to-ground tracking, refueling boom tracking, and formation flying. Other maneuvers, perhaps better suited to a particular airplane, may be invented as the need arises.

Formation maneuvers and refueling boom tracking maneuvers should not be flown so close to the lead airplane or to the refueling boom that the evaluation pilots feel that their safety is compromised by the high bandwidth HQDT piloting technique of aggressive, assiduous tracking.

With a single exception, a fixed pipper or aiming index is used during HQDT testing. When a moving pipper or aiming index is used (as in the case of a computing gunsight), the pipper (or gunsight) dynamics become a part of the evaluation. Our initial goal is to evaluate the dynamics of the pilot plus the airplane, rather than the pilot plus the airplane plus the gunsight. Hence a fixed pipper is nearly always used. The exception arises later, when it might prove desirable to evaluate the effect of the computing gunsight dynamics on handling qualities. Used in this way, HQDT can be an important tool for fine-tuning the gunsight component of the pilot-vehicle dynamics.

The depression angle of the pipper or aiming index is usually dictated by the airplane and the test maneuver. The depression angle may be set to minimize pendulum effect; or set to the angle that would be computed by the gunsight for a given load factor (in air-to-air tracking) or for a given dive angle (in air-to-ground tracking); or set to aid in avoiding the target airplane jetwake.

The test airplane must not be retrimmed during the test maneuver. Trimming detracts from the pilot's concentration on high bandwidth tracking and renders invalid a frequency response analysis of the test data (unless the trim imputs are recorded and made available for analysis).

<u>Pilot Evaluation</u> Pilot evaluation is the third component of Phase 2 HQDT testing. In HQDT testing, pilot comments are the most important part of the pilot evaluation, supported by a PIO rating. Careful and complete pilot comments from HQDT testing are the key to helping designers and flight test engineers understand the high bandwidth handling qualities of the airplane. Cooper-Harper ratings are not assigned following an HQDT evaluation because task performance (such as tracking error) is not measured during HQDT testing. Hence, it is

not possible to assign a legitimate Cooper-Harper rating based on an HQDT evaluation.

Phase 3: Operational Testing During Phase 3 testing the pilot conducts an operational evaluation of the airplane handling qualities. The purpose of Phase 3 testing is to determine whether the handling qualities are suitable for performing the various tasks that make up the design mission. Depending on the airplane, these tasks may include take-off, landing, aerial refueling, formation flight, and air-to-air and air-to-ground weapons delivery. Phase 3 operational testing must often be conducted in the presence of aggravating factors such as atmospheric turbulence, darkness, proximity to the ground, and so on. The risks associated with these factors must be explored in a build-up fashion. Cooper-Harper ratings are appropriate during Phase 3 operational testing.

Conclusion The overarching objective of the three phases of testing we have briefly described is to completely evaluate the full spectrum of airplane handling qualities. When we fail to achieve this objective, operational pilots become test pilots by default, but without the necessary preparation and safeguards we bring to bear in a properly conducted flight test program. For this reason, *the entire range of handling qualities must be explored by test pilots during flight testing, rather than by operational pilots during operational use of the airplane.*

At present, Phase 2 high bandwidth testing using HQDT test techniques is perhaps the most important tool we have for evaluating high bandwidth handling qualities characteristics, particularly PIO susceptibility. HQDT testing is often resisted or disparaged because its purpose and rationale are not understood, or because it has been used incorrectly by pilots who were not properly trained in the specialized HQDT piloting technique. When used properly, HQDT has proved to be uniquely successful. Properly conducted Phase 2 high bandwidth HQDT testing serves as a handling qualities "safety gate." If high bandwidth handling qualities prove to be satisfactory, it is unlikely that handling qualities will pose a significant safety of flight concern during operational use of the airplane. If PIO is not experienced during HQDT testing, it is unlikely that it will occur during operational use.

Pilot Opinion Ratings and PIO

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Two simple measures for dramatically improving the assessment of PIO susceptibility are presented, together with supporting arguments. These measures are first, to welcome, rather than suppress, the exposure of PIO susceptibility; and second, to assign a Cooper-Harper rating of 10 to every PIO, whether fully developed or incipient. A Cooper-Harper rating of 10 is a declaration that the airplane is uncontrollable during a PIO. It is argued that such a declaration is reasonable because pilots must *necessarily* relinquish control, if only temporarily, in order to arrest a PIO.

Discussion For more than 25 years, it has been possible to obtain reliable flight test assessments of PIO susceptibility using available test methods and rating scales. Yet reliable assessments are not the rule. We believe they could be made the rule by adopting two simple measures:

1. *Welcome, rather than suppress, the exposure of PIO susceptibility.*

2. *Assign a Cooper-Harper rating of 10 to every PIO, whether fully developed or incipient.*

We grant that adopting these two measures would require overturning long standing, deeply ingrained practice. But our experience suggests that traditional practice is misguided and counter-productive. We will discuss each of these proposed measures in turn.

Welcome the Exposure of PIO Susceptibility
PIO is not welcome during a flight test program. Consequently, pilots are under subtle but significant informal pressures to ignore, overlook, play down, or explain away occurrences of PIO. The reasons for these pressures are well known: a strong desire to maintain a success-oriented test schedule and budget; the fear of Congressional scrutiny; the fear that Congress will cancel a needed airplane, and so on. Because of these pressures an encounter with PIO can, in our experience, lead to a variety of pilot assessments. If the airplane is damaged or lost, the pilot would likely agree that a PIO occurred and a Cooper-Harper rating of 10 might be assigned (although in flight testing such a rating is uncommon). If the airplane is not damaged or lost, the pilot might not mention the PIO at all. Or the pilot might initially acknowledge that a PIO occurred, but later deny it. Or the pilot might acknowledge the PIO, but blame it on himself. (How many times have experienced handling qualities testers heard a pilot say: "I screwed up. If I hadn't ..., I wouldn't have gotten into a PIO.") Occasionally, a pilot will acknowledge the PIO and suggest that the airplane needs to be fixed, but the pilot who offers this assessment often suffers for his honesty.

We believe that the discovery of handling qualities deficiencies of every kind, including PIO, should be welcomed. The purpose of an acquisition program is to provide the operational users with an airplane that is suitable for performing the various tasks that make up the design mission. Line pilots rely on the test community to evaluate handling qualities thoroughly and objectively. They rely on the acquisition community to correct those deficiencies that warrant correcting (those that render the airplane unsafe or less than suitable). But these deficiencies cannot be corrected if they have not been found, or have been ignored or played down. Handling qualities deficiencies should be discovered by test pilots during the test program, not by line pilots during operational use. Test pilots should be given to understand that it is part of their job to discover strengths *and* deficiencies, and they should be lauded when they do. The discovery of an important deficiency should be regarded as an opportunity to provide a better finished product.

We should note in passing that following the YF-22 PIO incident, we at the Flight Test Center began to refer to PIO as "pilot-in-the-loop" oscillation, rather than "pilot-induced" oscillation. Pilots must be in the loop for a PIO to occur, but pilots *do not* induce these unwanted oscillations. If anything, it is the airplane that induces them. This is easily shown by noting that the same pilot, flying two different airplanes in the same manner may experience many PIOs in the one but never experience a PIO in the other. When pilots understand that PIO is not their fault, they are more likely to report occurrences of PIO and provide objective evaluations, comments, and ratings.

At present, PIO susceptibility is not always adequately explored and reported because test pilots and engineers recognize that PIOs are not welcome news. Perhaps the most effective way to immediately improve the assessment of PIO susceptibility is to welcome encounters with PIO during flight testing.

Assign Cooper-Harper Ratings of 10 to Every PIO We believe every PIO, whether fully developed or incipient, should be assigned a Cooper-Harper rating of 10. This is equivalent to saying that every PIO, whether fully developed or incipient, represents at least a temporary loss of control. We define fully developed and incipient PIOs in the following way. A fully developed PIO is one in which several cycles of the oscillation occur, even though the oscillation may not reach a visibly steady state. An incipient PIO is one which the pilot is able to recognize and quickly arrest, perhaps within a cycle or less.

Some in the handling qualities flight test community would agree that a fully developed PIO indicates a loss of control, and therefore warrants a Cooper-Harper rating of 10. But many would disagree, contending that when the pilot is able to arrest a fully developed PIO and continue with the task, control has not been lost, at least not in a long term, or global sense. They would further contend that a Cooper-Harper rating of 10 is warranted only when the PIO results in a stall, departure, collision with another airplane or the ground, or complete abandonment of the task. Few in the test community would agree that an incipient PIO warrants a Cooper-Harper rating of 10. If it can be shown that both fully developed and incipient PIOs represent a loss of control, then perhaps we can agree that every PIO should be assigned a Cooper-Harper rating of 10. We will turn our attention first to fully deveoped PIO, then to incipient PIO.

Fully Developed PIO Let us first explore the question of whether a fully developed PIO represents a loss of control. We begin by asking how a pilot arrests a fully developed PIO. One of three methods is usually employed: the pilot either freezes the controls, or releases the controls, or significantly reduces bandwidth (or the aggressiveness of control). When a pilot freezes or releases the controls, he has clearly relinquished control of the airplane for a time sufficient to arrest the PIO. Does it not follow that the pilot has also abandoned the task during the time required to arrest the PIO? While the controls are frozen or released, the pilot cannot be tracking the target, or controlling the flare, or whatever. If this is the case, we may ask why the pilot has abandoned the task if he still has control over the airplane. Isn't the answer that the airplane was uncontrollable during the PIO? When a pilot significantly reduces bandwidth to arrest a PIO, we would suggest that he has, in effect, transitioned from the primary task (tracking, landing, refueling, and so on) to the suddenly more important task of *regaining* control. We would even suggest that significantly reducing bandwidth is really another form of temporarily freezing the controls.

Implicit in our discussion is the understanding that when a pilot temporarily relinquishes control to arrest a PIO, he does so as a matter of necessity rather than choice. If it is *necessary* for the pilot to relinquish control in order to arrest a PIO and reestablish control, aren't we acknowledging that the airplane was temporarily uncontrollable? If the airplane was controllable, why did the pilot find it *necessary* to relinquish control?

Nevertheless, the objection will be raised that if a task is performed one hundred times and PIO is encountered only once, it would be silly to claim that the airplane is uncontrollable. We believe the proper rejoinder to this objection is a reminder that Cooper-Harper ratings are assigned to individual evaluations, or trials. If a PIO was experienced only once in one hundred evaluations of the same task in the same configuration at the same flight conditions, we would argue that the pilot lost control only once in one hundred evaluations, and that the airplane proved to be uncontrollable only once in one hundred evaluations, so that a rating of 10 was warranted only once in one hundred evaluations. This one data point out of a hundred is an important one that should not be swept under the rug or played down. If it can happen to a test pilot once in a hundred times, how often is it likely to happen to less experienced and possibly less skilled line pilots?

Incipient PIO Now let us turn our attention to the question of whether an incipient PIO represents a loss of control. In Figure 1 we present a sketch comparing time histories of pitch rate response and stick force during two events of interest. In one event, represented by dashed line time histories, we see a fully developed PIO. In the second event, represented by solid line time histories, we see an incipient PIO. Both PIOs were precipitated by identical circumstances. At the first arrow, nose down pitch rate begins to develop and the pilot counters by nudging the stick aft, but without apparent effect (perhaps because of excessive phase lag), so that nose down pitch rate continues to increase. The pilot continues to smoothly increase countering stick force until, suddenly, at the second arrow the airplane begins to pitch up rapidly. In an attempt to arrest this rapid and unsettling reversal of motion the pilot takes action. In the PIO represented by the dashed line time histories, the pilot makes a moderately large and rapid control input in the opposite direction, which aggravates the airplane response and causes the pilot to transition from low to high bandwidth control. A fully developed PIO ensues. In the PIO represented by the solid line time histories, the pilot adopts a different course of action. Recognizing that a PIO is about to begin, the pilot makes a small corrective input to arrest the unwanted motion and then relinquishes control by freezing the stick. After a short interval (perhaps a second or two, perhaps only a fraction of a second), the pilot gets back into the loop and resumes flying the airplane. Note that there is no visible evidence of PIO or PIO susceptibility in the solid line time histories of this incipient PIO. Only the pilot is aware that he intentionally relinquished control in order to avoid the PIO he sensed was about to ensnare him. When flying an airplane that is PIO susceptible, it is not uncommon for pilots to repeatedly relinquish control to forestall PIO.

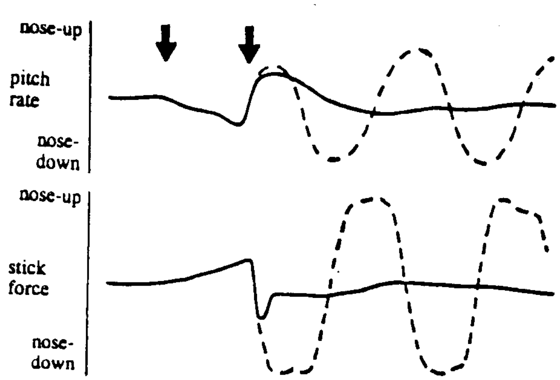

Figure 1 *A comparison of two events.*

What distinguishes the events recorded in the dashed line time histories from those recorded in the solid line time histories? In the dashed line time histories, the pilot remained in the loop and allowed himself to be drawn from low bandwidth control into high bandwidth control, resulting in a fully developed PIO. In the solid line time histories the pilot made a small corrective input and then temporarily relinquished control of the airplane until the unsettling motion subsided, thereby avoiding any visible evidence of PIO or PIO susceptibility. But we see in this second case that the pilot *did embark on a PIO*, before quickly arresting it by temporarily relinquishing control. In other words, a PIO was encountered in both cases: in the one, the PIO became fully developed, whereas in the other the PIO was incipient. In both cases, we believe the airplane should be described as PIO susceptible.

Most pilots and engineers would argue that the event recorded by the solid line time histories in Figure 1 is simply an example of pilot compensation, and indeed we acknowledge that this is so. By temporarily relinquishing control (a form of compensation), the pilot succeeded in arresting the PIO at the incipient stage, before it could become fully developed. As every experienced pilot knows, when an airplane has poor handling qualities, temporarily relinquishing control can be a very effective form of pilot compensation. Skilled, experienced pilots know when to exercise control and when to leave well enough alone. When poor handling qualities are in evidence, it has been observed that the best pilots are those who exercise the most forethought and the least control. Unfortunately, this form of compensation may hide serious deficiences from everyone but the pilot, who may choose not to mention them. Our concern is that, by regarding the temporary relinquishing of control as compensation, the pilot is hiding the fact that an airplane is PIO susceptible. We believe that when control must, *of necessity*, be temporarily relinquished to arrest or forestall PIO, whether incipient or fully developed, the airplane must be regarded as temporarily uncontrollable. To regard it otherwise is to risk assessing the PIO susceptibility of pilots rather than airplanes.

Conclusion For more than 25 years, it has been possible to obtain reliable flight test assessments of PIO susceptibility using available test methods and rating scales. However, many pilots and engineers have deduced from flight test practices that PIO encounters are unwelcome. Available test methods and rating scales are not always used, or are used in a compromising manner, rendering them less effective; and subtle pressures may be brought to bear on pilots, encouraging them to ignore, overlook, play down, or explain away PIO encounters. We are presently quite capable of thoroughly and accurately assessing PIO susceptibility, but we believe that such assessments will not become routine until two simple measures are adopted: first, welcome the exposure of PIO; and second, assign a Cooper-Harper rating of 10 to every encounter with a PIO, whether fully developed or incipient.

To some, it will seem Procrustean to insist that every occurrence of PIO be assigned a Cooper-Harper rating of 10. After all, this is a declaration that the airplane is uncontrollable, which is a harsh word. Nevertheless, the strategy for arresting a PIO is to temporarily relinquish control, which leads us to the question: if an airplane is controllable, why should it ever be *necessary* to relinquish control? When control is given up of *necessity*, doesn't this mean that the airplane could not be controlled, and is therefore uncontrollable, even if only temporarily? Although the strategy of temporarily relinquishing short term control in order to preserve long term control may legitimately be described as pilot compensation, doing so serves to camouflage PIO susceptibility. The pilot may recognize what he is doing, but he is unlikely to mention it to anyone else.

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The workshop “Pilot-Induced Oscillation Research: The Status at the End of the Century,” was held at NASA Dryden Flight Research Center on 6–8 April 1999. The presentations at this conference addressed the most current information available, addressing regulatory issues, flight test, safety, modeling, prediction, simulation, mitigation or prevention, and areas that require further research. All presentations were approved for publication as unclassified documents with no limits on their distribution. This proceedings includes the viewgraphs (some with author’s notes) used for thirty presentations that were actually given and two presentations that were not given because of time limitations. Four technical papers on this subject are also included.

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